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SOLID STATE RADIOGRAPHIC IMAGE AMPLIFIERS PART B

By Zoltan Szepesi

Westinghouse Electric Corporation
Electronic Tube Division
Elmira, New York

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16. ABSTRACT

This report describes the second part (Part B) of the program for the development of solid state radiographic amplifiers. The developed solid state image amplifiers are intended as equivalent or improved replacements for fluoroscopic screens and X-ray film used in radiographic evaluations of space vehicle components and structures. Non-storage type radiograpic amplifiers similar to fluorescopic screens were built with improved sensitivity and contrast. A simple photoconductor-electroluminescent (PC-EL) type radiographic storage amplifier was developed with high resolution (higher than 300 line/inch), long image storage (5 minutes to 1 hour) and medium radiation input sensitivity (1 röntgen input for suitable image). The high contrast sensitivity obtained closely approached the 2% of thickness definition per MIL-STD-453, for 0.25" thick aluminum plate (2% penetrameter outline visible). Light sensitive storage amplifiers were developed as potential replacements for "X-Y" type area scan-recorders, when used with a high-intensity point light source input. A simple PC-EL construction was developed with an ASA sensitivity of 10^{-2}, and a cascaded construction with more than ten times higher sensitivity but with lower resolution. Compact power supplies were also built for these image amplifiers.

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GLOSSARY

Brightness	Measure of visual sensation of luminous intensity. It is often used instead of luminance or luminous emittance.
Color Temperature	The equivalent temperature of a black body radiation, whose chromaticity is approximately the same as that of the light source in question.
Electroluminescence(EL)	Luminescence excited by an electric field or current.
Footcandle (fc)	Unit of illumination. Equal to the luminous flux (in lumens) received on 1 square foot of the illuminated surface.
Gamma (γ)	Measure of the image contrast of an intensifier panel. It is equal to the slope of the transfer characteristics drawn on double logarithmic paper: $\gamma = \frac{d\ (\log B)}{d\ (\log L)}$ (where L is the input light intensity, B is the output brightness).
Illumination	Density of the luminous flux on an illuminated surface. Its units are the footcandle (lumens per square foot), lux (lumens per m^2) and phot (lumens per cm^2), 1 fc = 10.764 lux = 1.0764 mphot (milliphot = 10^{-3} phot).
Image Amplifier or Image Intensifier	Device for increasing the brightness of an image. Two varieties of such image intensifiers are under development. (1) Vacuum tube type, using photoelectric emission, electron optics, and cathodoluminescence; (2) Solid state type, using PC and EL materials.
Lumen (lm)	Unit of luminous flux. It is equal to the flux through a unit solid angle (steradian) from a uniform point source of 1 candle.
Luminance	Light intensity per unit of projected point of source. Its units are: candle/cm^2, candle/ft^2, etc.
Luminescence	Phenomenon of light emission caused by any effect other than high temperature (thermal radiation), as electroluminescence (EL), photoluminescence (PL), bioluminescence, cathodoluminescence, etc.
Luminous Emittance	Luminous flux emitted per unit area. Its units are lumen/cm^2 (Lambert), lumen/ft^2 (footlambert).
Luminous Flux	The total visible energy emitted by a source per unit time. Its unit is the lumen.

Luminous Gain	The ratio of the total output flux in luminous units to the corresponding input flux in the same units. The input spectrum, the output phosphor, and the input or output flux level must be specified.
Photoluminescence(PL)	Luminescence excited by electromagnetic radiation as ultraviolet, or visible light, or X-rays.
Resolution	Measure of the optical quality of an image, regarding the separation of close elements. Its units are: (1) optical lines per inch; (2) line-pairs per inch; (3) TV lines per inch; and (4) elements or cells per inch. Units (3) and (4) differ by a factor of two from units (1) and (2), e.g.: a resolution of 50 optical lines (or simple optical resolution of 50 lines) per inch, 50 line-pairs per inch, 100 TV lines per inch and 100 elements or cells per inch are equivalent statements.
Röntgen (R)	Unit of X-ray dose. R/sec and R/min are units of X-ray intensity.
Spectral Distribution (of emission)	The power distribution of emitted light as a function of the wavelength. Given generally in relative units, with the maximum value as 100%.
Spectral Response (of photoresponsive elements or devices)	Dependence of photosensitivity (photocurrent or output) on wavelength of illuminating light. Measured generally by recording the output of the photoresponsive device when irradiating it with a constant power of monochromatic light of changing wavelengths. If the dark output is not negligible, its value is subtracted from the measured outputs. The spectral response curve is given generally in relative units, the maximum of the curve being set to 100%. If the slope of the output-input light intensity curve is not constant, the spectral response curve depends on the intensity of the monochromatic illumination. To eliminate this variable, another measuring method should be used; preferably, the power of the monochromatic light is adjusted so that a constant output is obtained when changing the wavelength. The reciprocal value of this illuminating power as a function of wavelengths will give the spectral response curve.
Standard Luminous Gain	Same as luminous gain if the input flux is 2870°K color temperature tungsten lamp radiation.

<u>Sublinear-Curve (or function)</u>	Where the absolute value of the slope (first derivative) is decreasing with increasing abscissa (independent variable). If the function is of the form $y = c\,x^n$, it is sublinear when $n < 1$. Note that $n = d(\log y)/d(\log x)$ and see "Gamma".
<u>Superlinear or Supra-linear Curve (or function)</u>	Where the absolute value of the slope (first derivative) is increasing with increasing abscissa (independent variable). If the function is described by the equation: $y = c\,x^n$, it is superlinear when $n > 1$.
<u>Transfer Characteristics</u>	Curve representing the output brightness as a function of the input light intensity of the image intensifier. Drawn generally on double logarithmic paper.

ABBREVIATIONS AND SYMBOLS

Å	-	Angstrom = 10^{-8} cm = 10^{-10} m (10^{-1} nm)
AC	-	alternative current
B	-	brightness in footlamberts
B_o	-	constant of EL cells
C	-	capacitance
CdS	-	cadmium sulfide
CdSe	-	cadmium selenide
DC	-	direct current
EL	-	electroluminescent, electroluminescence
ε	-	dielectric constant
f	-	frequency in Hz
fc	-	footcandle
fL	-	footlambert
G	-	gain
γ	-	measure of contrast
Hz	-	Hertz, unit of frequency
I	-	current
I.I.	-	image intensifier
k	-	kilo = 10^3, e.g.: kHz = 10^3 Hz
L	-	light intensity in footcandles
λ	-	wavelength
m	-	meter
M	-	mega - 10^6 e.g.: MΩ = $10^6\Omega$
μ	-	micro = 10^{-6} e.g.: μm = 10^{-6} m
μm	-	micrometer = 10^{-6} meter (used instead of micron)
n	-	nano - 10^{-9} e.g.: nm = 10^{-9} m

P	-	capacitance ratio
PC	-	photoconductive, photoconductor
RMS	-	root mean square
R	-	resistance or Röntgen
S.S.	-	storage screen
σ	-	conductivity
t	-	thickness of layer
T	-	temperature
V	-	Volts, voltage
W	-	watt
Ω	-	ohm

SUMMARY

The work in this second part of the contract was directed toward the development of (1) storage radiographic amplifier screens, (2) flexible radiographic amplifier screens, (3) highly sensitive radiographic amplifiers without storage, and (4) light sensitive storage image amplifiers. The developed radiographic amplifiers are intended as equivalent or improved replacements for fluoroscopic screens and X-ray film used in radiographic evaluations of space vehicle components and structures. Light sensitive storage amplifiers were developed as potential replacements for "X-Y" type area scan-recorders, when used with a light-intensity point light source input.

8" x 10" size radiographic storage amplifier screens were fabricated both on glass substrates and on plastic substrates. They were built in a simple photoconductor-electroluminescent (PC-EL) sandwich type construction with ZnO as the sensing material. The minimum exposure for obtaining an acceptable image on these screens was about 1 röntgen. The resolution was 300 to 500 lines/inch (6 to 10 line pairs/mm). The storage time was (to 1/3 brightness) between 5 minutes to 1 hour, depending on the preparation of the ZnO and on other construction parameters. The erasure of the image was achieved by heating the panel in a furnace or by electrical heating of a panel electrode. It needed one to ten minutes depending on the storage time of the panel.

The non-storage higher sensitivity panels similar to fluorescent screens, were constructed in a PC-EL sandwich structure also, but the PC layer was sintered CdS-CdSe powder. Threshold sensitivities were lower than 60 mR/minute (1 mR/sec).

The contrast sensitivity of both type of radiographic amplifiers closely approached the 2% thickness definition per MIL-STD-453, for 0.25" thick aluminum plate (2% penetrameter outline visible).

The flexible radiographic storage screen, built on the "Aclar" plastic was not satisfactory due to delamination of the substrate from subsequent deposited layers. However, a flexible panel is a feasible approach, which was demonstrated in the laboratory, but some work remains to be done on substrate adherence, optimum substrate thickness, and elastomeric binders with compatible coefficients of expansion.

Light sensitive storage panels were successfully developed. The two different approaches which evolved were: (1) using a non-storage PC-EL image intensifier (CdS-CdSe) in combination with a Thorn image retaining panel; (2) using a light sensitive ZnO photoconductor in a simple PC-EL sandwiching construction.

Promising experiments were made by sandwiching a non-storage radiographic amplifier panel with a light sensitive storage panel of the ZnO type. Also, experiments with photographic film exposure in contact with a solid state radiographic amplifier improved the contrast sensitivity. One approach to meet reasonably high requirements would be by integrating in one unit two cascaded image amplifiers. Dark-field EL panels would

bring also improved characteristics when the panel is viewed in ambient light. The use of evaporated El films is also recommended in view of the possibility of higher contrast sensitivity.

SECTION 1

INTRODUCTION

This report gives an account of the work performed on Contract No. NAS8-21206, Part B, from June 1, 1968 to November 30, 1969. The work carried out from July 1, 1967 to April 30, 1968 on the first part of the contract, Part A, is reported in the Final Report on Solid State Radiographic Image Amplifiers[1] edited in May 1968. Some sections of this report are repeated here, making the present report more self-contained.

In the first part of the contract a solid state storage radiographic image amplifier system was developed for the direct viewing of radiographic images. The development was based on techniques resulting from a program on light sensitive image intensifiers[2-6] supported by the Naval Training Device Center, Orlando, Florida*. The radiographic amplifier system consisted of the combination of a photoconductor-electroluminescent (PC-EL) type image amplifier and an image retaining panel, made by Thorn Electrical Industries, Ltd. in England. This system ideally combined reasonably short exposure time with long storage and fast erasure. However, there were some inconvenient characteristics in this system and therefore it was recommended that work be continued for (1) improving uniformity and reducing spottiness; (2) increasing contrast sensitivity; (3) integrating the storage in the amplifier unit; (4) eliminating the effect of ambient light; and (5) constructing the system from space qualified components. A continued program was planned considering these recommendations.

The work on this program was performed at the Electronic Tube Division of the Westinghouse Electric Corporation, Elmira, New York by M. A. Novice, E. E. Selby, C. A. Lepkowski, and R. Chalmers, with Z. Szepesi as project engineer. W. Stürmer was consultant in problems of fabrication methods. Managerial supervision was provided by G. W. Goetze, R. A. Shaffer, and A. B. Laponsky.

The project engineer of this contract at the Marshall Space Flight Center was R. L. Brown, followed by J. Beal.

*Contract Nos. N61339-562, N61339-1440, and N61339-66-C-0064.

SECTION 2

OBJECTIVES

The objectives of this work were:

(1) to improve contrast sensitivity of radiographic amplifiers,

(2) to build storage properties into a single radiographic unit,

(3) to develop flexible radiographic amplifiers, and

(4) to build light sensitive image amplifiers with storage.

The resolution of the image amplifier panels should be not less than 200 lines/inch (4 line pairs/mm). The goal for contrast sensitivity should be 2% of specimen thickness in accordance with MIL-STD-453. The storage time should be at least 5 minutes and the erase time not longer than 2 minutes. The developed radiographic amplifier system shall be capable of operating in normal terrestrial environment between -25°C and 50°C, furthermore in a 100% oxygen atmosphere of 5 psi and in vacuum of 10^{-6} Torr. They shall be oriented toward use in radiographic non-destructive testing equipment used in terrestrial and space environment evaluations of space vehicle structures and components. The selection of materials and components of the image amplifier system must be made with future space hardware requirements in mind.

Table 1 lists the image amplifiers and other equipment which were to be delivered to the Marshall Space Flight Center (MSFC) at the end of the work program.

Item	Quantity	Size
Radiographic image amplifier with storage	2	8" x 10"
Higher sensitive radiographic image amplifier (non-storage)	2	6" x 9"
Flexible radiographic amplifier with storage	1	8" x 10"
Light sensitive image amplifier without storage	4	4" x 6"
Thorn image retaining (storage) panels	4	4" x 6"
Battery operated power supply for above panels.	3	250 inch^3
Spare batteries for power supply	3	---

TABLE 1. HARDWARE TO BE DELIVERED TO MSFC

SECTION 3

METHOD OF APPROACH

The image amplifiers, both the X-ray sensitive and the light sensitive type, developed in this program are of the photoconductor-electroluminescent (PC-EL) sandwich type construction.

The history of this type of amplifier goes back to 1952 when it was invented. Four independent patent applications were made in this year: the first in Germany (W. Stürmer, Philips)[7], the second in Australia (Amalgamated Wireless Ltd.)[8], and the last two in the United States (E. W. Vaughn - E. L. Webb - M. E. Hayes, Westinghouse Electric Corporation[9] and W. C. White, General Electric[10]). Since then patents in the order of a hundred were awarded proposing a large variety of construction techniques, materials, and applications.

Figure 1 shows the basic circuit: The sensor element, a photoconductor (PC), is connected in series with the display element, an electroluminescent (EL) cell. An AC voltage is necessary to obtain high brightness and good efficiency on the EL layer.

The first condition for an acceptable image amplifier is that the brightness of the EL element be very low when the input light intensity is zero. To obtain this, the impedance of the PC element should be much higher than that of the EL element. This requires not only a high dark resistance of the photoconductor, but a high capacitance ratio of the EL to the PC element, i.e. $C_{EL}/C_{PC} \gg 1$. Since the voltage is divided between the EL and PC elements as the impedance ratio, in this case the EL element will have a low voltage and consequently a very low light output.

The brightness B of the EL cell is described by the following formula:

$$B = B_o f^{\alpha} \exp \left(- A/V_{EL}\right),$$

where B_o, α and A are constants for a given cell, f is the frequency of the driving voltage, (α is near to unity), and V_{EL} is the voltage on the EL cell.

When the PC element is illuminated, its resistance decreases, the voltage across the EL element increases and the output light is increased. If the PC cell is sensitive to the light emitted by the EL cell, a positive feedback is present which can give increased light output, or, if the gain at the emitted wavelength is high enough, results in a bistable device, In this case the output light stays on after the input light is switched off, thus this pehnomenon enables one to make storage displays. But without special construction the light feedback can cause lateral spreading and resolution loss. An opaque film placed between the PC and EL elements will eliminate this feedback effect.

The PC-EL circuit without light feedback has an S-shaped transfer characteristic as shown in Figure 2 on a double logarithmic scale. The

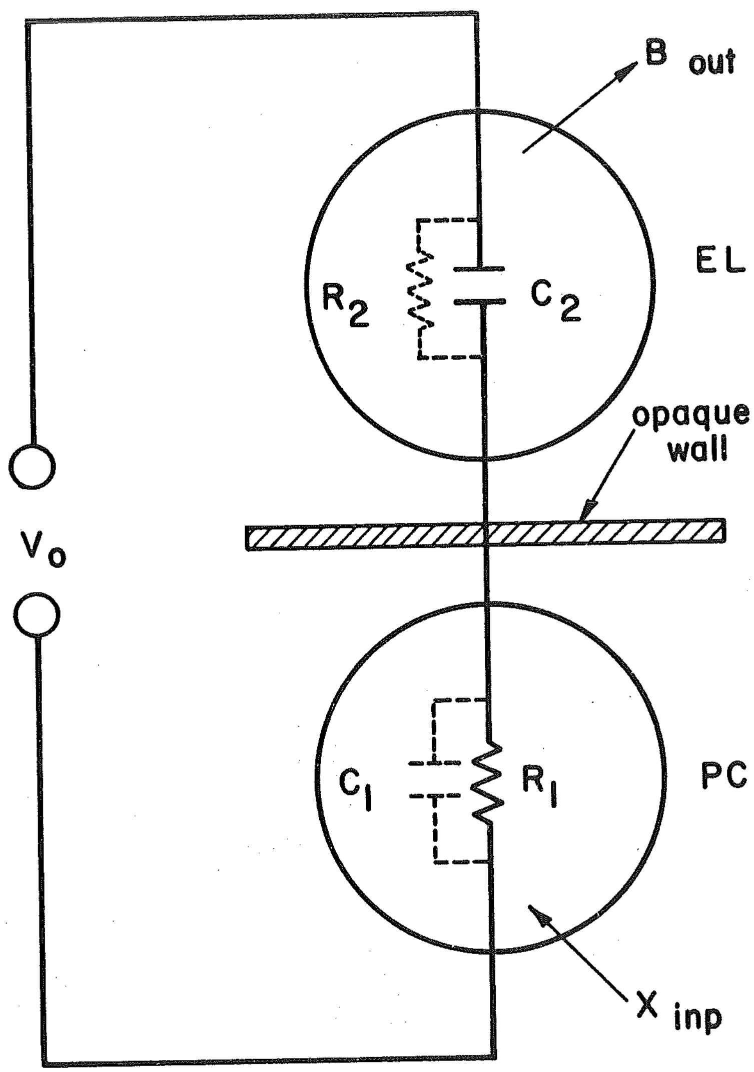


FIGURE 1: Basic Circuit of PC-EL Type Light Intensifiers

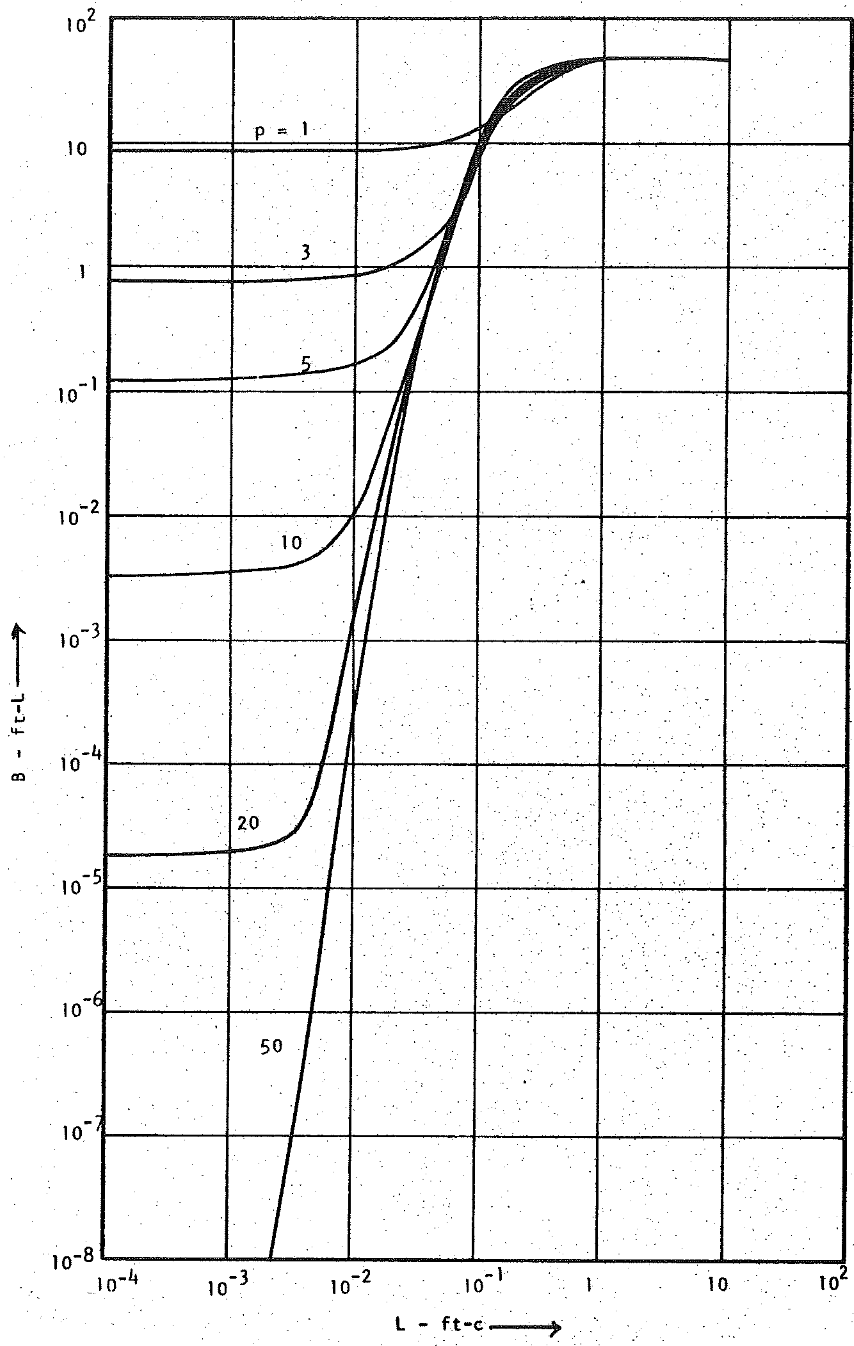


FIGURE 2: Calculated Transfer Characteristics of PC-EL Image Amplifiers With Different Capacitance Ratios: $p = C_{EL}/C_{PC}$

parameter in this figure is the capacitance ratio $p = C_{EL}/C_{PC}$. These curves show that the background light is diminishing and the maximum contrast is increasing with increasing capacitance ratio.

If the optoelectronic characteristics of the PC and EL cells are properly chosen, the light output could be higher than the input within a given intensity region and light intensification is achieved.

By building a two dimensional mosaic array of such PC-EL pairs, an image amplifier can be constructed. Also, continuous thin layers of the PC and EL materials sandwiched between two electrodes, should in principle, give a well working image amplifier. The first patents, cited above, described just this construction. However, it was difficult to satisfy the requirement of the high capacitance ratio of the EL to the PC layer. Luminous gain in the order of unity was the highest obtained with this sandwich type construction[11]. The problem was caused by the fact that for high enough capacitance ratio a thick PC layer was required and such a layer in volume conduction (through the thickness) had low light sensitivity, because the light was absorbed in a very thin layer on the surface. It was only recently that high dielectric plastic materials were available for the embedment of the EL powder, thus luminous gains in excess of ten lumen/footcandle were achieved in this sandwich construction at Westinghouse[2].

The continuous layer sandwich type construction is the most simple and ideal way to fabricate solid state image amplifiers. Figure 3 shows construction details of such a practical working panel. The PC layer is deposited on a tin oxide coated glass plate. It could be a plastic embedded CdS, CdSe powder, or a mixture of the two, but the best results were obtained with sintered CdSe layers. Its thickness could be between 100 and 150 μm (4 to 6 mils). The intermediate semiconductive film has a higher donor concentration than that of the contacted PC layer, offering thereby an ohmic contact. Consequently electron injection and high gain can be obtained in the PC layer. The black layer is an evaporated cermet film (MgF_2+In). However, this layer is not needed if the PC layer has low response to the EL light. The conductivities of both the semiconductive and the black films must not be excessive to prevent spreading of the current in lateral direction. The EL layer is ZnS (Cu,Br), embedded in a high dielectric constant plastic. An evaporated PbO-Au film serves as the top electrode of the panel.

Such a panel, as all the other PC-EL types, can be used as image amplifier in the visible waveband if the PC material is sensitive in this region. If the PC material has sensitivity in the infrared, ultraviolet or X-ray region, the panel can be used as an infrared converter, ultraviolet converter, or radiographic amplifier screen respectively.

CdS and CdSe are sensitive PC materials in the visible, near infrared and X-ray region, consequently the image amplifiers using these materials are infrared converters and radiographic amplifiers also. Table 2 lists some characteristics of such panels developed in the first part (Part A) of this program.

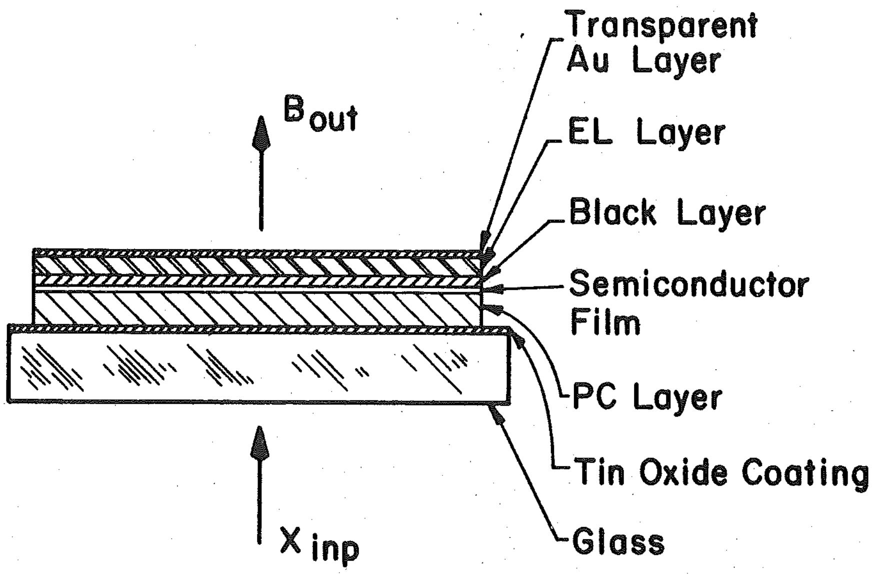


FIGURE 3: Construction of a PC-EL Sandwich Type Image Amplifier

CHARACTERISTICS	MEASURED DATA	UNITS, ETC.
Size	8" x 10"	Square Inches
Resolution	180	TV Lines/Inch
Threshold	2×10^{-2}	fc (2870 K source)
	or 500	mröntgen/min. at 80 keV
	or 10^{-8}	W/cm^2 at $\lambda = 0.85\ \mu m$
Output at Threshold	5×10^{-4}	fL
Maximum Output Brightness	1 to 10	fL, depending on frequency
Maximum Contrast (γ)	2 to 5	
Maximum Luminous Gain	10 to 100	fL/fc (2870 K source)
Decay Time Constant	100	msec at maximum gain
Rise Time Constant	1000	msec at maximum gain

TABLE 2. CHARACTERISTICS OF AVERAGE PC-EL IMAGE AMPLIFIERS

3.1 Storage Radiographic Amplifier Screens

In the first part (Part A) of this program, storage radiographic amplifiers were built by cascading two separate panels(1): first a non-storage type PC-EL radiographic amplifier, as described above, and second a Thorn image retaining panel*. The fact that the Thorn image retaining panel is built on an opaque metal substrate caused two inconvenient characteristics of this system; first, the image could not be checked during exposure, and second, the stored image was a mirror image, which could be seen only after separating the two panels. Also a loss in resolution resulted from the lack of intimate contact of the two panels.

At the beginning of Part B of this program an appreciable effort was made to develop the Thorn panel on a transparent substrate for eliminating the two above-mentioned inconvenient features. Also, it was hoped that by this development a construction of the two panels in one single unit will be possible. However, the results of this effort were not satisfactory and other methods for achieving storage were considered.

Various other ways for obtaining storage in solid state image amplifiers have been described and demonstrated (see page 4 of Ref. 1). After studying the different approaches for satisfying the requirements of this contract, it was concluded that the most promising solution would be to build a PC-EL sandwich type construction with a photoconductor having a long decay time. The use of CdS for this purpose was described by Stürmer(12). A panel obtained

*Made by Thorn Electrical Industries, Ltd., Enfield, England.

from him and several others made by us were examined and studied. It was found that the image deteriorated too fast in the beginning of the decay and less than 1 minute storage time could be obtained with acceptable image brightness. Therefore, other photoconductors were examined for suitability in this application.

Excellent storage properties of fine grained ZnO powders have been described by Ruppel, Gerritsen, and Rose[13]. Also, Dr. Stürmer at Siemens has built storage radiographic amplifiers using ZnO as the sensing element. An experimental panel, obtained from him, worked very satisfactorily. Therefore, this approach was chosen for building the storage radiographic amplifier panel. As work progressed, information was received that Dr. P. Ranby at Thorn Electrical Industries was also developing a radiographic image storage panel. An experimental panel, obtained from him and also from the Yosemite Laboratories, Oakland, California showed very similar characteristics.

The X-ray sensitive ZnO has very low sensitivity for visible light, which results in an appreciable convenience in working with these panels. Also, there is no need to apply an electric field to the panel during exposure. The panel is energized only if one wants to see the image. A good quality image can be viewed continuously for 5 to 30 minutes, depending on the preparation of the ZnO powder. The resolution of these panels is better than 300 TV lines/inch (6 line pairs/mm), and panels even with 500 TV lines/inch resolution were made. This storage panel is very simple to fabricate, consequently it is inexpensive. It should be noted here that "storage time" refers to the total time the panel is energized for viewing. When the panel has been exposed, but not energized, it will hold the image for many hours without appreciable reduction in brightness, resolution and contrast when the viewing period begins.

The stored image can be erased by heating the panel in a furnace of about 100 C (212°F) for 2 to 30 minutes, depending on the storage capability (panels with short storage need shorter baking). Erasure time is the main inconvenience of ZnO storage panels. However, a faster way of erasing the image was found by heating electically (approximately 5 minutes at 50 volts) one electrode of the panel. In practice, using 2 or 3 panels successively, the time inconvenience could be diminished and no delay would result from the slow erasure.

3.2 Flexible Panels

Since in the construction of the storage radiographic amplifier screen, described in the previous section (3.1), no high temperature processing is needed, it is possible, in principle, to fabricate a flexible storage panel in the same construction as that of the non-flexible type by substituting sheet plastic for the glass substrate.

After examining several plastic materials, a fluorohalocarbon called "Aclar"* (of 0.005" thickness) was chosen. It was available in different thicknesses for a moderate price and satisfied the requirements for this

*Trade name of Allied Chemical, General Chemical Division construction, i.e. it withstood an hour baking at 135°C (275°F) temperature, retaining suitable flatness and having good adhesion to the EL layer at the time of fabrication. Furthermore the Aclar is the most resistant plastic to water vapor penetration, thereby protecting the EL layer from fast deterioration. Smaller size (2" x 2") panels withstood appreciable bending (less than 2" radius) in both directions. Large 8" x 10" panels, however, deteriorated from repetitive bending when the thin plastic substrate delaminated from the deposited layers and the top electrode lost is conductivity. The completed panel also eventually wrinkled and warped and would not lay flat. Some work remains to be done on substrate adherence, optimum thickness of flexible substrate, and elastomeric binders with compatible coefficients of expansion.

The details of the fabrication of the flexible panel will be discussed in Section 4.

3.3 High Sensitivity Radiographic Amplifier Without Storage

A radiographic amplifier having high absolute sensitivity would have an important role in some applications. However, for industrial non-destructive testing the high contrast sensitivity is the first requirement in order to attain the 2-2T quality specified in MIL-STD-453.

A PC-EL sandwich type construction with CdS-CdSe sensing layer (PC) was the most promising approach to satisfy these requirements.

A series of experiments was carried out for fabricating this panel similar to that of the storage type, i.e. build all component layers in plastic embedment, so that no high temperature handling is needed. However, these plastic embedded panels showed high,unacceptable graininess and low contrast. Since radiographic amplifiers built on sintered CdS-CdSe photoconductors offered much better characteristics, the plastic embedded construction was discontinued and most of the effort was directed toward meeting the requirements with the sintered PC layer construction.

From previous experiments it was known that the sensitivity of the CdS-CdSe type photoconductors be increased by building higher donor and lower acceptor concentration into the crystal structure. Also, it was known that for obtaining high slope in the current vs. radiation intensity characteristics (needed for high contrast in the amplifier panel), a high acceptor concentration in the PC crystal structure is necessary. Thus the requirements for maximum sensitivity and maximum contrast are incompatible and a compromise has to be accepted.

In the beginning of the work the main effort was on developing panels with high absolute sensitivity, but later the main emphasis was on the high contrast sensitivity.

3.4 Light Sensitive Storage Panels

CdS and CdSe have much higher sensitivities in the visible wavelengths than ZnO. Therefore it was decided to build light sensitive panels with CdS-CdSe. CdS was the material of higher preference for this application, because its spectral response curve covers a larger part of the visible spectrum and also it has longer decay time, i.e. longer storage than CdSe. However, as it was mentioned in the discussion on radiographic storage panels, here also it was found that the image deteriorates too fast and therefore the storage time is insufficient.

Because, during the majority of this program, built-in light sensitive storage was not realizable, Thorn image retaining panels were provided to be combined with the developed light sensitive CdS-CdSe image intensifier panels, thereby obtaining the required storage. This method was already developed in the first part of this contract for radiographic amplifiers[1], thus it was certain that it would work similarly with light sensitive image intensifiers.

Besides this approach, a minor effort was directed toward the construction of light sensitive storage panels in another way. Some experiments were carried out successfully in sensitizing ZnO with organic dyes for the visible waveband and PC-EL panels were built with these ZnO powders. They showed good storage characteristics, however, the sensitivity was quite low. With further work the sensitivity could be increased and these storage panels would find practical applications, as indicated in Section 7.

SECTION 4

FABRICATION TECHNIQUE

Fabrication technique and construction details of the different panels together with those of the power supply will be described in this Section.

4.1 Radiographic Amplifiers

Three types of radiographic amplifiers were developed:

(1) Storage radiographic amplifiers on rigid substrate.

(2) Storage radiographic amplifiers on flexible substrate.

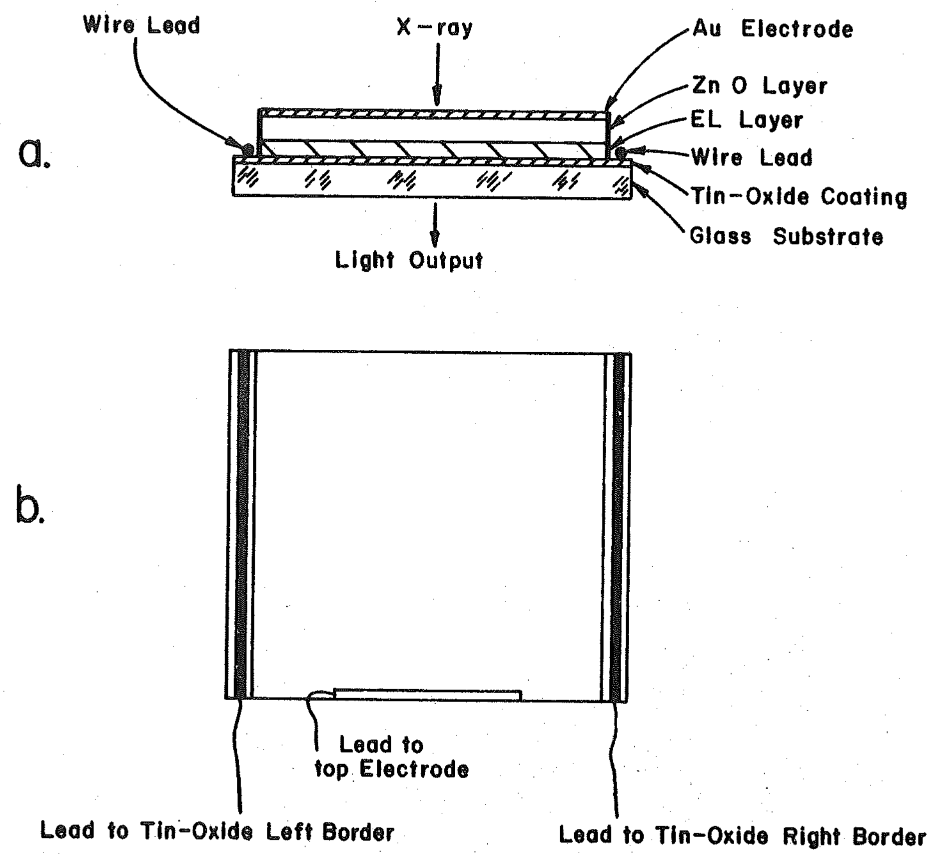
(3) Non-storage type radiographic amplifiers.

All three types were fabricated essentially in a sandwich construction made up of two principal layers: the PC and EL layers as Figure 3 shows. However there were differences in some details. Consequently the construction technology is described separately.

4.1.1 Storage Radiographic Amplifiers on Rigid Substrate. The construction of these screens is shown in Figure 4, and the detailed step by step fabrication method is described in Appendix D. A short account of the fabrication is given in the following paragraphs. The EL layer is sprayed first on the tin-oxide coated glass substrate. It is a high dielectric plastic embedded ZnS(Cu, Br) powder. The ZnO layer is doctor bladed on the top of the EL layer (See Appendix D). It is also plastic embedded, but the plastic is a silicone resin and has a low dielectric constant. The thickness of the EL layer is between 1 and 2 mils (25 to 50 μm) and that of the PC layer is 8-10 mils (200-250μm). The choice of the thicknesses and dielectric constants results in a high capacitance ratio C_{EL}/C_{PC}, needed to have low background light and high contrast. The top electrode is an evaporated gold film, about a μm thick. It does not need to be transparent to visible light, but it is to X-rays.

Two opposite edges of the tin oxide coating have a low resistant connecting lead (see Figure 4(b)) which serves for the electric heating of the panel. The third lead is the top electrode. The driving voltage (50 to 400 Hz) is connected between this electrode and any of the tin oxide leads when one wants to display an image.

It seems that ZnO is not irreversibly damaged in humid atmosphere, but it is known that the brightness of the EL layer deteriorates rapidly when activated in humid atmosphere. Therefore, an attempt was made to protect the panel by sealing a glass plate on top of it. However, the sensitivity of the sealed panel dropped considerably and the dark current increased. Consequently this protective sealing could not be used. It is thought that the ZnO needs free oxygen and probably a layer which can offer this will have to be applied within the sealed construction. A series of experiments will be needed to find the proper material which can satisfactorily solve this problem.



(a) cross section (b) top view

FIGURE 4: Construction of Storage Radiographic Amplifier Screens on Glass Substrates

The gradual brightness deterioration of the EL layer occurs only when the electric field is applied and current is flowing. The absorption of humidity during the time period when the panel is not used does not cause any problems; the humidity can be evaporated by heating the EL layer and no change can be noticed up to this point. Consequently, the brightness decrease will be slower when the panel is used after such treatment. Fortunately, the heating process is necessary for image erasing on the storage radiographic amplifier and thereby the deterioration of the EL brightness is slowed down, if the heating is applied immediately before each use of the panel.

4.1.2 Storage Radiographic Amplifier on Flexible Substrates. In the fabrication of the storage radiographic amplifiers, as described in the previous paragraphs, both the PC and EL layers are plastic embedded and the maximum temperature during the production of these panels is 135°C. Consequently this technique is adoptable for the fabrication of flexible storage radiographic amplifiers.

The construction of the flexible panel is in principle the same as that of the solid panel. The substrate is a plastic sheet, which can withstand 135°C heating for an hour, without appreciable changes, with good adhesion to the EL layer. Kel-F* was tried without success, but Aclar** met the requirements, at least when small area panels were made. A semi-transparent PbO-Au-PbO layer was evaporated first on a 5 to 7 mils thick Aclar sheet. The EL layer was sprayed as well as the ZnO layer. Here thinner ZnO layer (about 4 mils) had to be used for good flexibility, and the spraying method proved to be applicable. The doctor-blading requires a very flat surface and the flatness of the EL coated Aclar was not good enough for doctor-blading. To fabricate larger area panels on plastic substrates some changes in the choice of materials have to be made.

Electric heating of the flexible radiographic amplifier was not considered, because of the fragile evaporated gold layers. However, it is possible that this method eventually could be used on the flexible panel too.

The construction of the flexible radiographic amplifier is shown in Figure 5, and the detailed fabrication process is described in Appendix D.

4.1.3 Non-Storage Type Radiographic Amplifiers. The construction of the radiographic amplifier screen without storage is also a PC-EL sandwich type. The PC layer is here a sintered CdS-CdSe powder, and it is deposited first on the tin-oxide coated glass. Figure 3 shows the principal construction. Figure 6 gives details of the completed panel and Appendix E describes the detailed fabrication schedule.

* Trade name of MMM Company

** Trade name of Allied Chemical

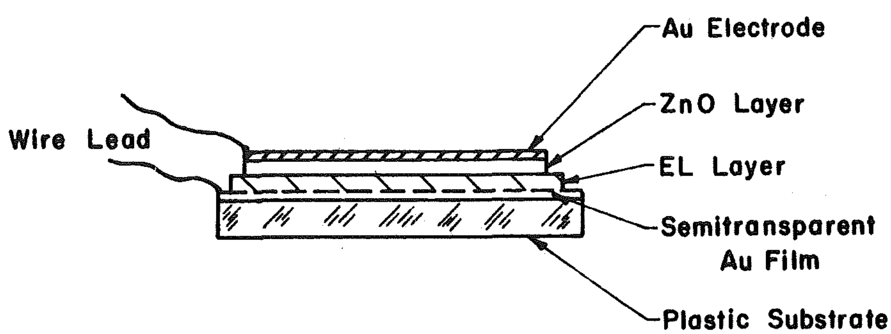
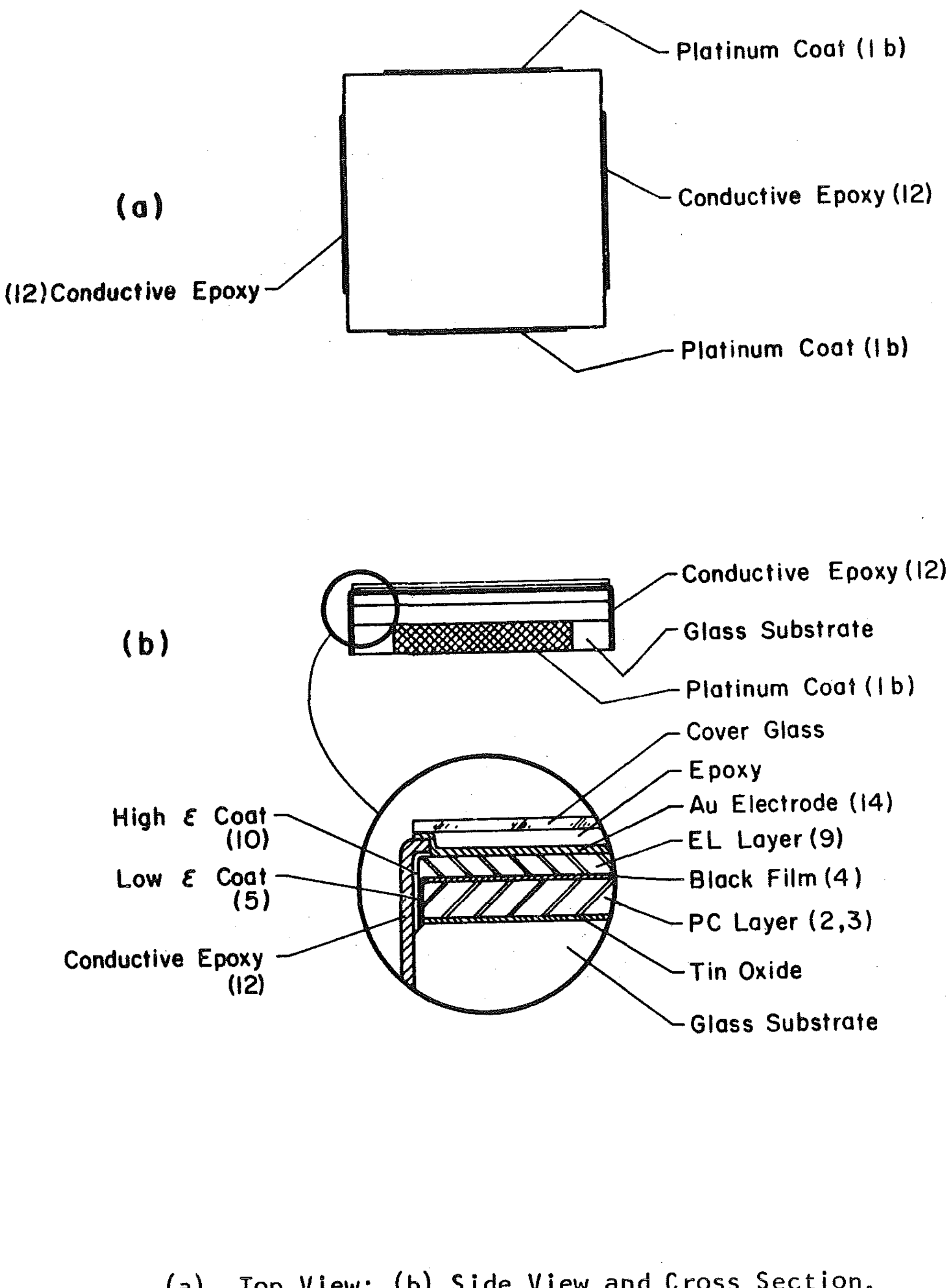


FIGURE 5: Construction of Flexible Storage Radiographic Amplifier Screens



(a) Top View; (b) Side View and Cross Section.
Numbers in Parentheses refer to Appendix C.

FIGURE 6: Construction Details of Non-Storage Type Radiographic Amplifiers

During the period of this reported work, many variations of PC powder compositions were evaluated. CdS-CdSe mixtures were used in proportions of 1:9, 1:3, and 1:1. Also, the amount of $CuCl_2$, which supplies the acceptor impurity and influences the absolute sensitivity and contrast of the amplifier panel, was varied between 0.022 and 0.040%.

Results of these experiments were as follows: (1) Decreasing the amount of CdSe increases the time constant and the spectral response in the visible band is displaced toward the shorter wavelengths, as shown in Figure 7. Also, more copper chloride is needed for the same sensitivity. (2) For a given CdS-CdSe mixture the increase of the copper impurities increases the contrast, but decreases the sensitivity, the dark current, and the decay time constant.

The best compromise for contrast and sensitivity was a mixture of CdS to CdSe in 1 to 3 proportion with 0.035% $CuCl_2+2H_2O$ by weight. The delivered panels were made with this mixture.

4.2 Light Sensitive Panels

Two approaches were developed for the light sensitive storage panel. The first, a combined system, was a light sensitive non-storage PC-EL type panel superimposed on a Thorn image retaining panel. The second, developed late in the program,was a simple PC-EL construction with dye-sensitized ZnO as PC material.

4.2.1 Combined System. The non-storage PC-EL light sensitive panel had a CdS-CdSe sintered layer as the sensor. The construction of the panel was exactly the same as that of the non-storage type radiographic amplifier and it is described in Appendix E.

The image retaining panel was purchased from Thorn Electrical Industries, Great Cambridge Road, Enfield, Middlesex, England.

In the combined system the image retaining panel, which is on a metal plate, is placed with its front side in contact with the output (EL) side of the PC-EL panel during exposure. After exposure, the image retaining panel is separated from the non-storage panel and shows the projected picture. This is a mirror image of the picture shown on the output of the PC-EL panel.

4.2.2 Single PC-EL Storage Panel. The construction of the light sensitive storage PC-EL panels is the same as that of the radiographic storage panels and is described in Appendix D. In the light sensitive panel, however, an organic dyed ZnO powder is the sensing layer. The composition and preparation of the light sensitive powder is described also in Appendix D.

4.3 Power Supplies

Three power supplies were constructed, numbered 2, 3, and 4. (Power supply No. 1 was delivered in Part A of the program). They supply the necessary voltages for the different amplifier panels: Nos. 2 and 3 for

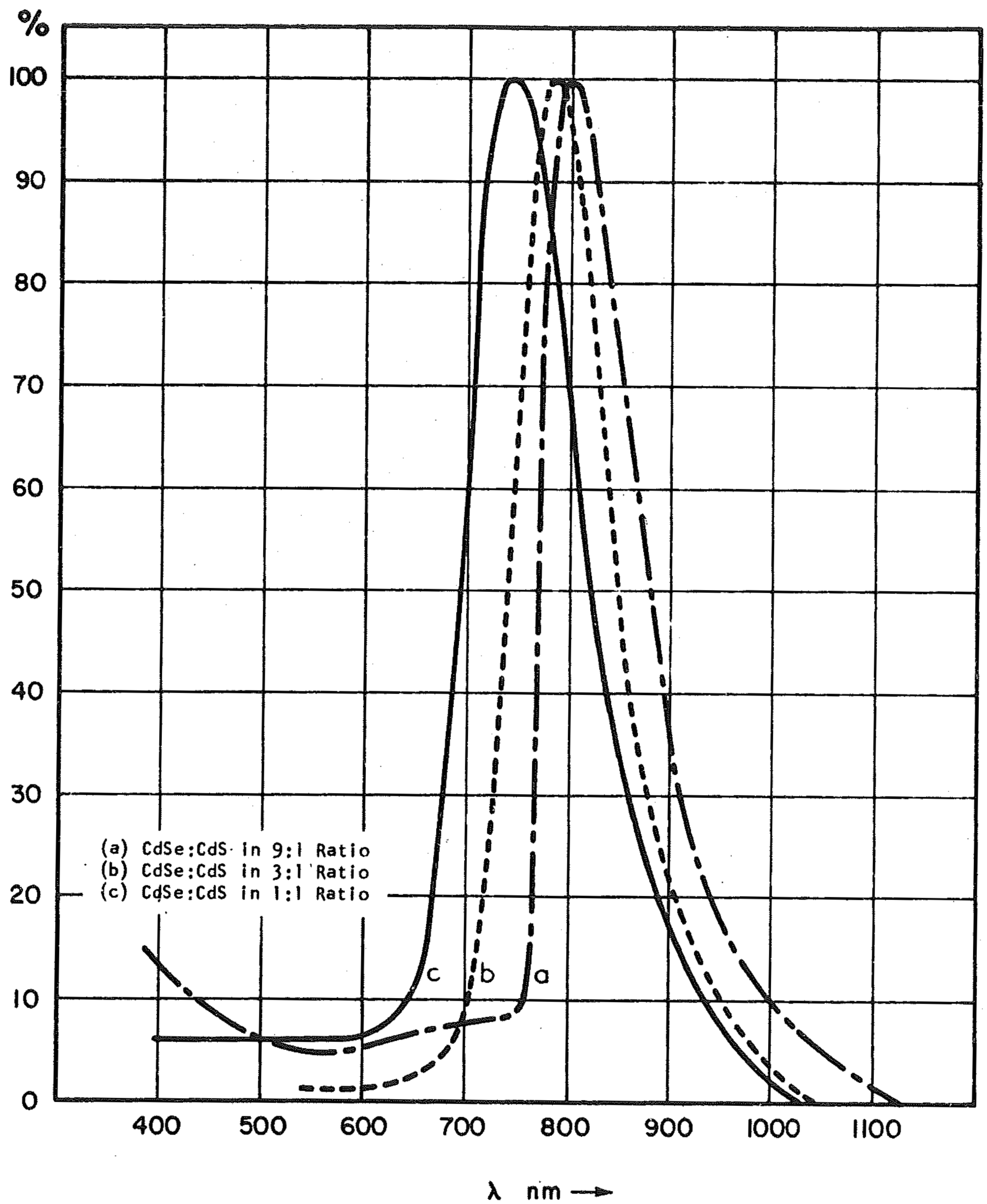


FIGURE 7: Spectral Response of CdS-CdSe (Cu-Cl) Sintered PC Layers in Volume Conduction

non-storage type radiographic and light sensitive storage amplifiers (giving AC and DC voltages), and No. 4 for the radiographic amplifier panels with storage.

In the construction of these power supplies the portability (small weight and size) was the leading objective. Their volume is 225 cubic inches each. Their weight is slightly more than 11 pounds each.

The block diagram of the power supplies is shown in Figure 8. Circuit diagrams of protection circuits are in Figures 9 and 10. Details of the power supplies and list of parts are presented in a separate Instruction Manual.

Besides the power supplies, a heating unit is constructed for image erasure of storage ZnO panels. It consists principally of a solid state light dimmer. The block diagram of the unit is shown in Figure 11.

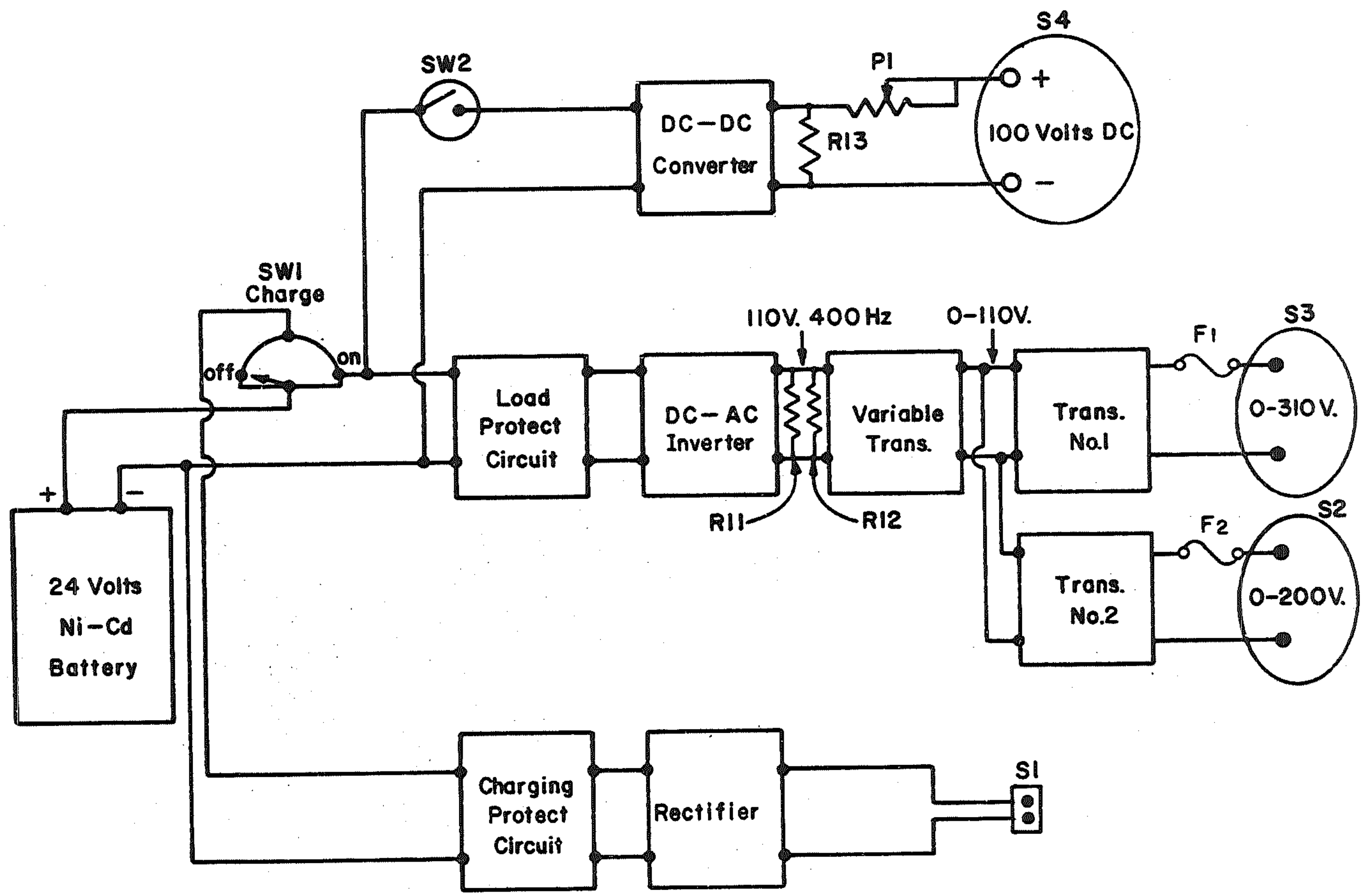


FIGURE 8: Block Diagram of Power Supply Unit

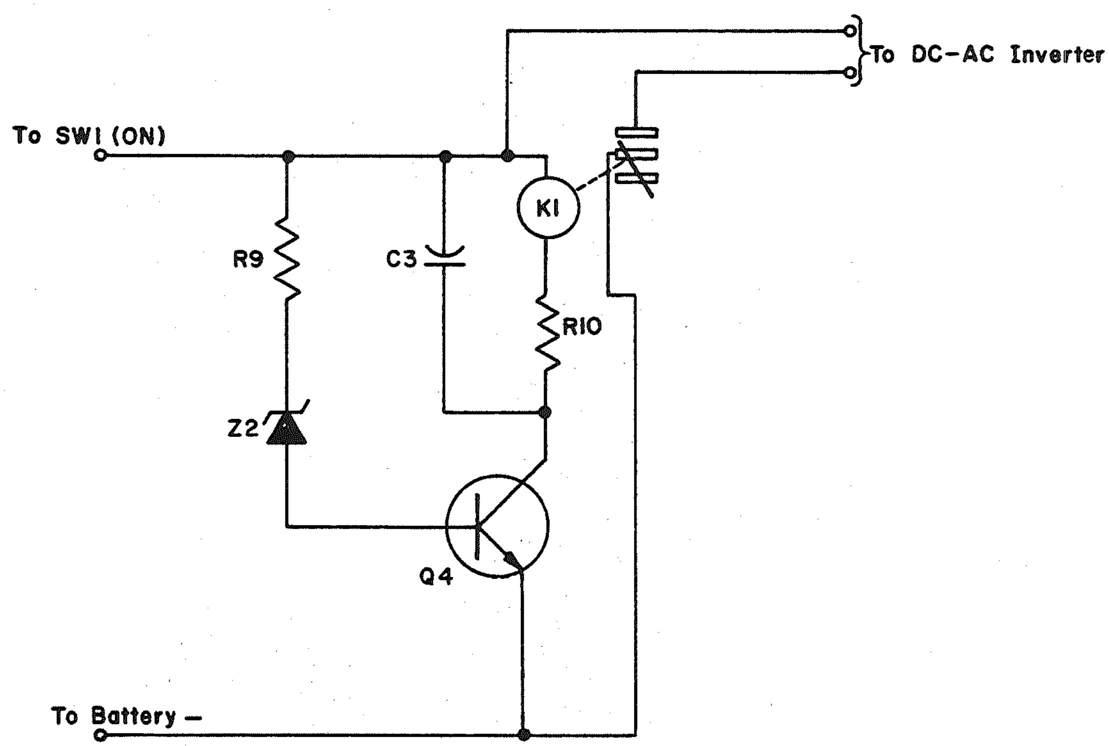


FIGURE 9: Load Protection Circuit

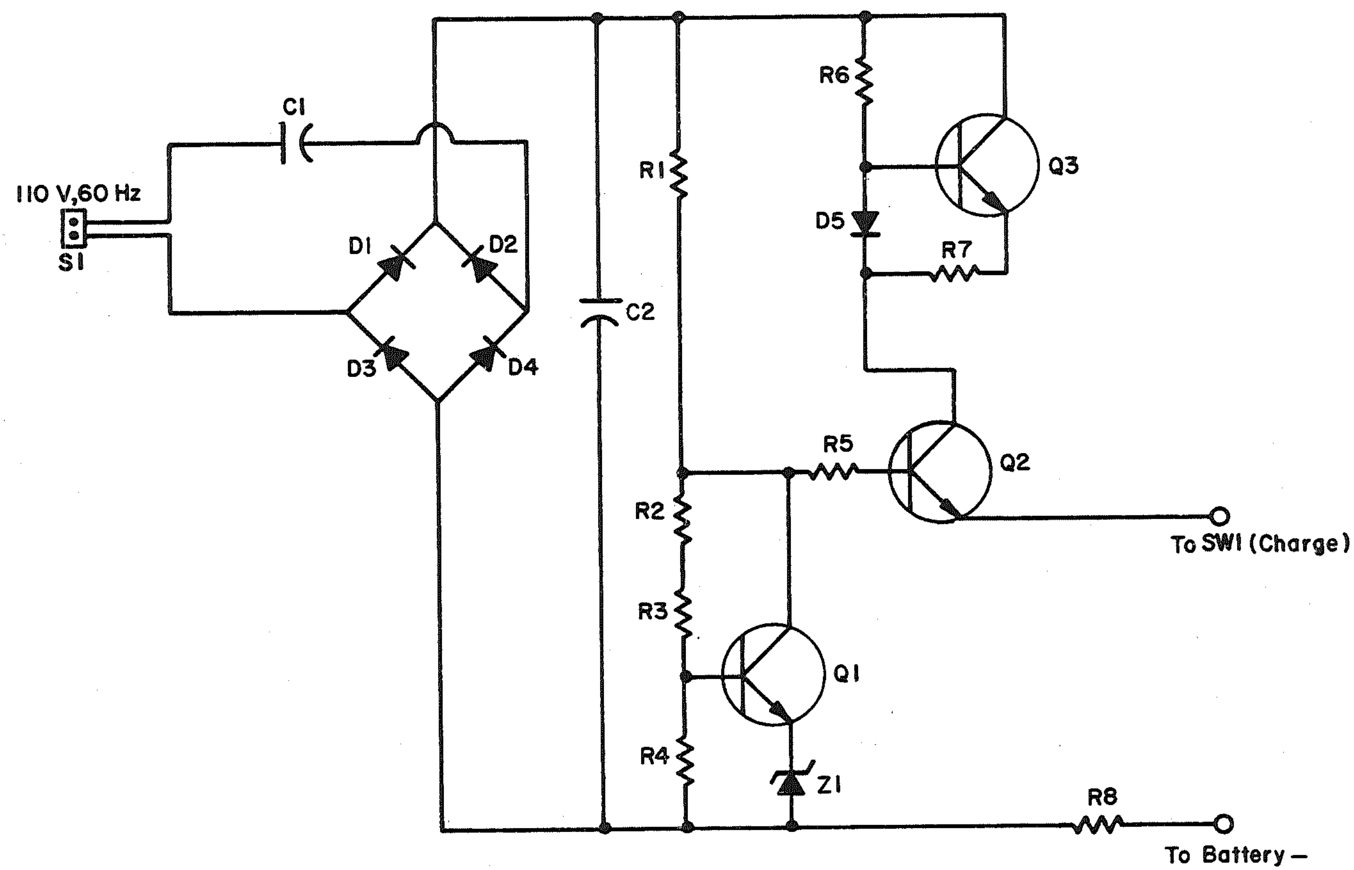


FIGURE 10: Charge Protection Circuit

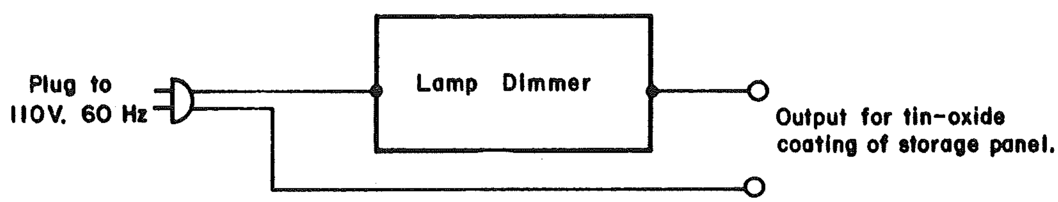


FIGURE 11: Block Diagram of Storage Panel Heating Unit

SECTION 5

CHARACTERISTICS

During the development work amplifier panels in all categories were fabricated with a wide range of characteristics. The data, presented in this section, are measured on individual panels, representing average characteristics, which can be reproduced with good yield. Amplifier panels were made with better and worse values in some characteristics.

5.1 Radiographic Amplifiers

The first requirement for both storage and non-storage type radiographic amplifiers was to have high contrast sensitivity. The goal was the detection of the 2T holes of a 2% penetrameter per MIL-STD-453, on 1/4" thick aluminum. The outline of the penetrameter could be easily detected with both non-storage and storage type amplifier panels, but the small holes could not be seen. However, some experiments, carried out by taking contact prints on photographic paper from the output of the amplifier screen, showed the outline of the penetrameter with a highly increased contrast. The loss of resolution in the contact printing explains why the small holes were not visible. Experiments carried out under better conditions (higher current, lower voltage input) may result in the detection of the 2T penetrameter holes. This view is supported by the fact that the resolution of both types of radiographic amplifiers was in the order of 300 lines/inch or better. This means that 10 times finer lines could be detected than the diameter of the 2T holes of the penetrameter (20 mils).

In the beginning of the program on Part B, some effort was directed toward the development of non-storage type radiographic amplifiers with higher absolute sensitivity. The X-ray intensity required for threshold activation of the most sensitive panels was lower than 20 mR/min or 0.3 mR/sec. Figure 12 shows the transfer characteristics of such panels.

The sensor material of these amplifiers was a CdSe-CdS mixture in 9:1 ratio sensitized with Cl and Cu. The Cu content in the mixture powder was lower than the previously used amount (0,02% against 0.025%). As it was expected, the contrast sensitivity of these panels was not better than that of the previously standardized panels.

Therefore, in the following part of the program the effort was directed toward increasing the contrast sensitivity regardless of other characteristics. In this work series of experiments were made with PC powders containing larger amounts of acceptor impurities (Cu). Measured transfer characteristics did not show much change in gamma and the visual detectibility was not improved. The absolute sensitivity and the dark current of these panels decreased very much. With increased amounts of CdS in the PC micture the contrast improved somewhat, but the absolute sensitivity was again low. Figure 13 shows transfer characteristics of one of these panels where the CdSe:CdS ratio was 3:1 and the copper chloride was 0.035%. Figure 14 is a photograph of the output image,when an etched stainless steel sheet was radiographed.

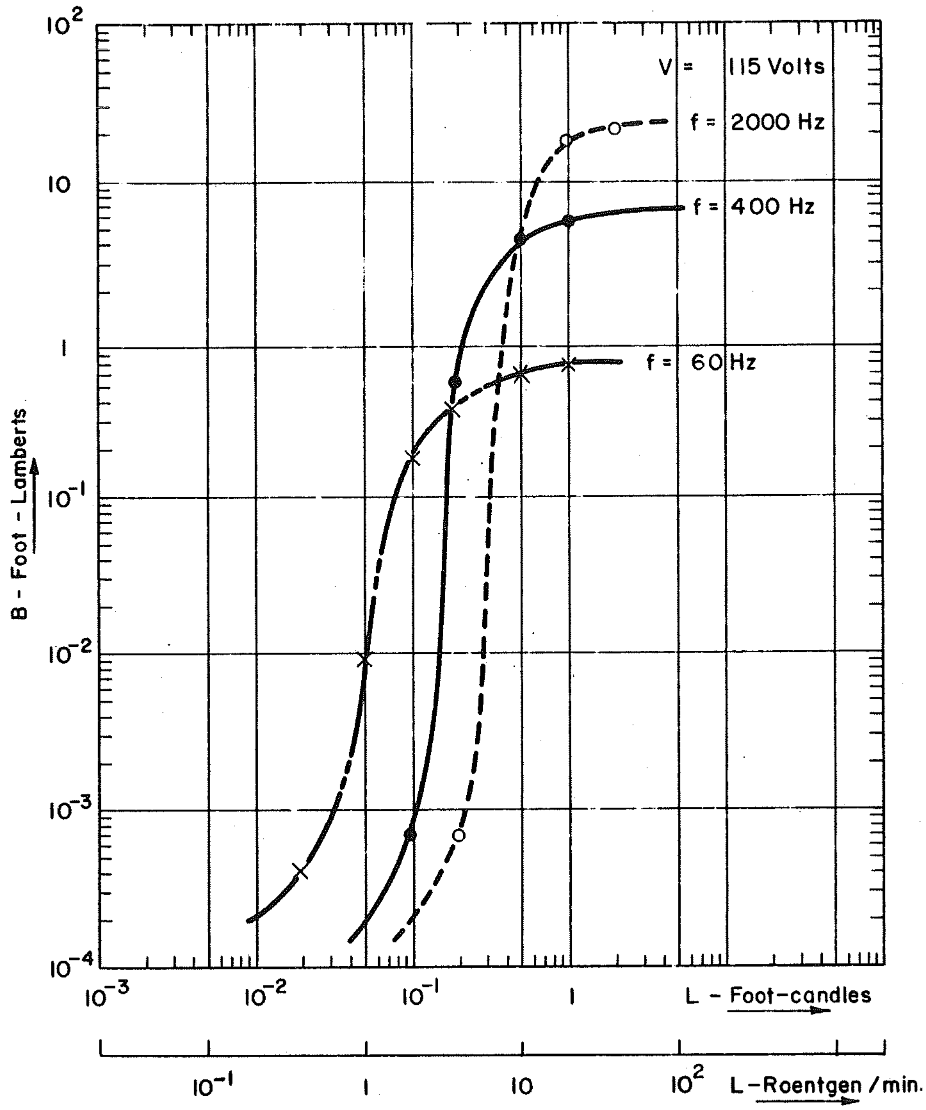


FIGURE 12: Transfer Characteristics of Non-Storage Type High Sensitive Radiographic Amplifiers

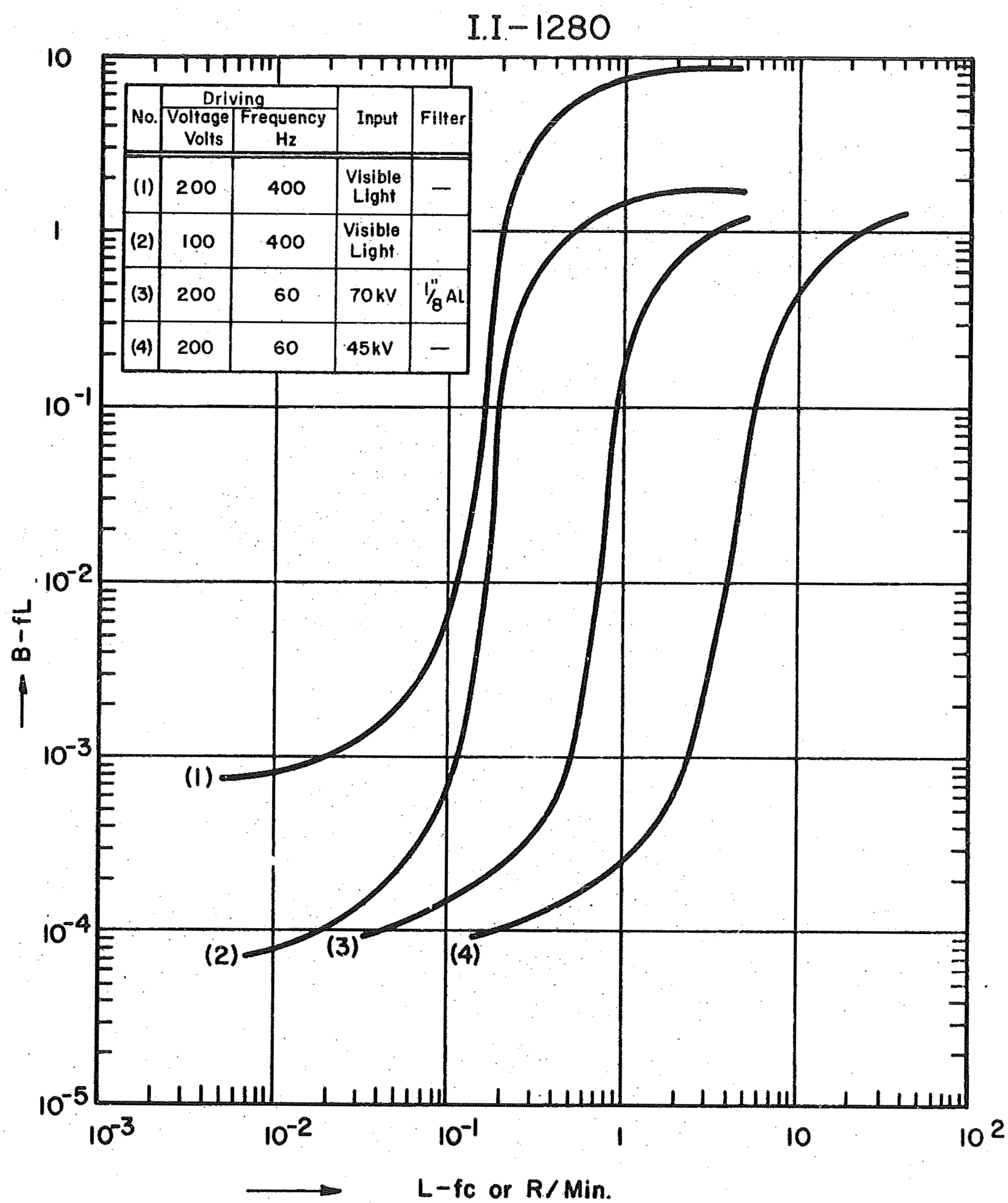


FIGURE 13: Transfer Characteristics of a Non-Storage Radiographic Amplifier With High Copper Doping

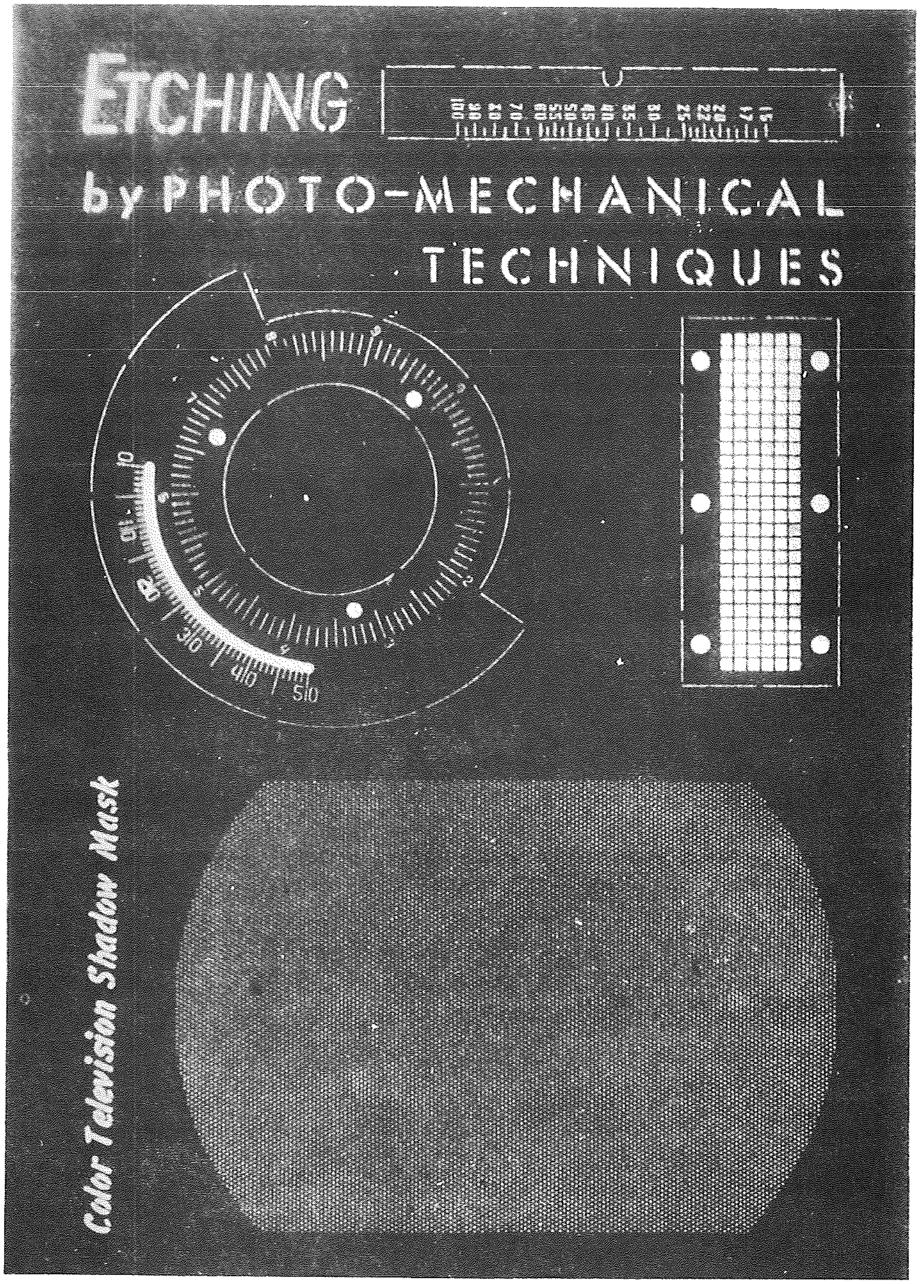


FIGURE 14: Photograph of a Radiographic Image on a Non-Storage Type Amplifier

The contrast sensitivity of the storage type radiographic amplifiers was about the same as that of the non-storage type panel. Their absolute sensitivity could be deduced from a record of the brightness change with time (see Figure 15). The panel in the first minute was irradiated with about 35 R/min X-ray intensity (45 kV unfiltered radiation). We see that the threshold dose was about 1 R and the decay time to 1/2 of the maximum brightness was about 47 minutes. Storage panels with shorter and longer decay times were also fabricated. The driving frequency in the measurements was 60 Hz. Using higher frequencies the storage time decreased.

The erasure time of these panels, by baking them in a furnace at 100°C (212°F) was between 5 and 15 minutes, shorter for the panels with shorter storage time. Electrical heating of the tin-oxide coating shortened the erasure time by a factor of 2 or 3.

5.2 Light Sensitive Panels

Non-storage type light sensitive panels were made with CdSe:CdS mixtures in 3:1 and 1:1 proportion.

Transfer characteristics of one of these panels is shown in Figure 16, and a photograph of the output image of a TV test pattern is shown in Figure 17. These panels, used in combination with a Thorn image retaining panel,offered the required storage system.

Simple PC-EL storage type light sensitive panels were constructed with dyed ZnO powder. Their threshold sensitivity measured with a 2870°K tungsten light source was about 10 fcs (footcandle-second), i.e. about 100 mcs (meter-candle-second). This means and ASA sensitivity of 10^{-2}. The storage time of these panels was 10 minutes or longer. They had good resolution (higher than 200 lines/inch).

5.3 Power Supplies

Two of the power supplies contained a DC-DC converter, giving 100 Volts DC for driving the Thorn image retaining panels. Two of them contained the charging protection circuit and one of these also had a load protection circuit. One of them contained two AC transformers with outputs of 200 Volts and 310 Volts. Table 3 shows these differences.

Power Supply No.	Load Protection Circuit	Charging Protection Circuit	DC-DC Converter	Transformer		Weight	
				No. 1 Volts	No. 2 Volts	Lbs.	Ozs.
2	No	No	Yes	0-310	0-200	11	6
3	No	Yes	Yes	No	0-200	11	4
4	Yes	Yes	No	0-310	No	11	1

TABLE 3. COMPONENTS AND WEIGHTS OF POWER SUPPLIES

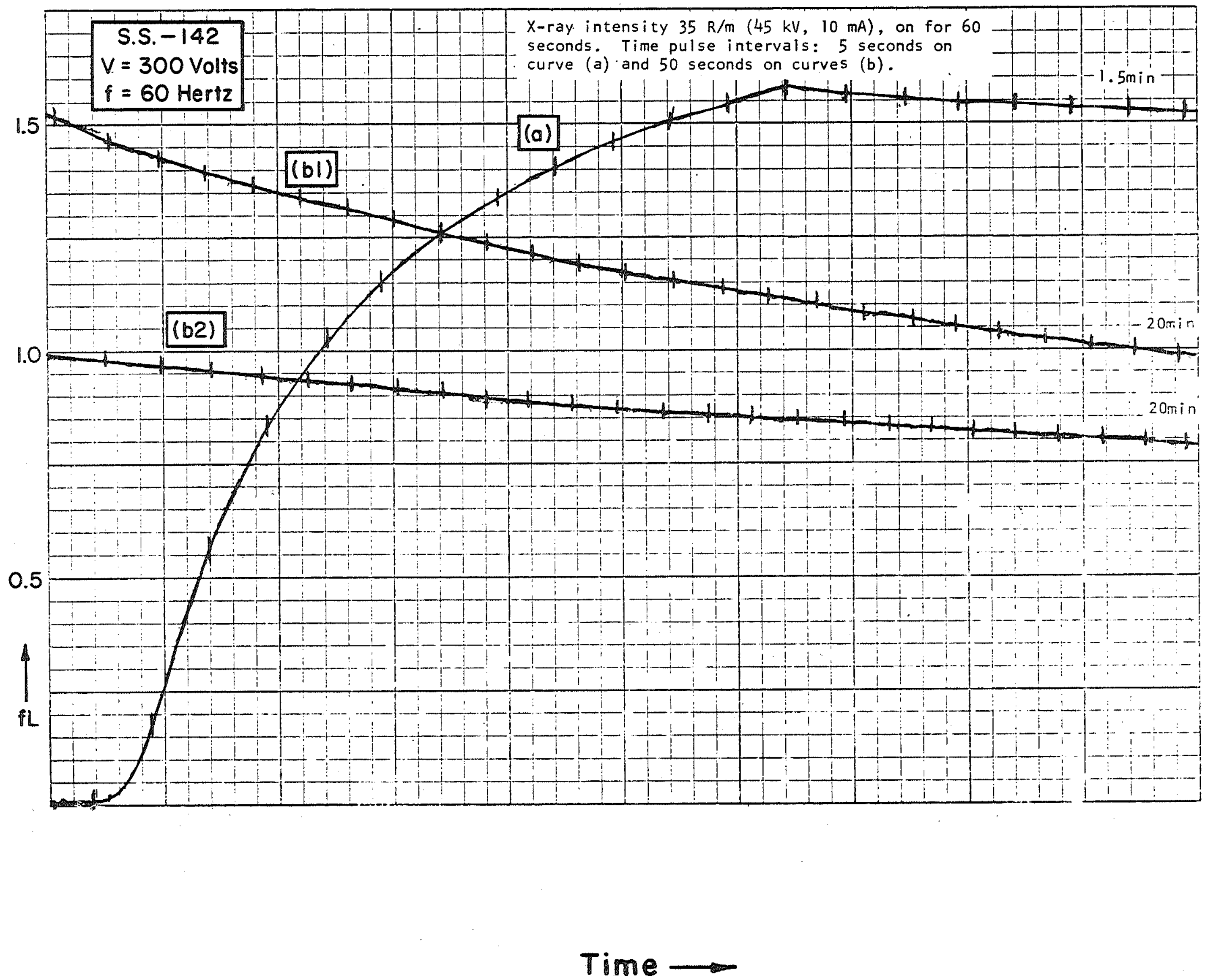


FIGURE 15: Output Brightness vs. Time Record of Storage Type Radiographic Amplifiers

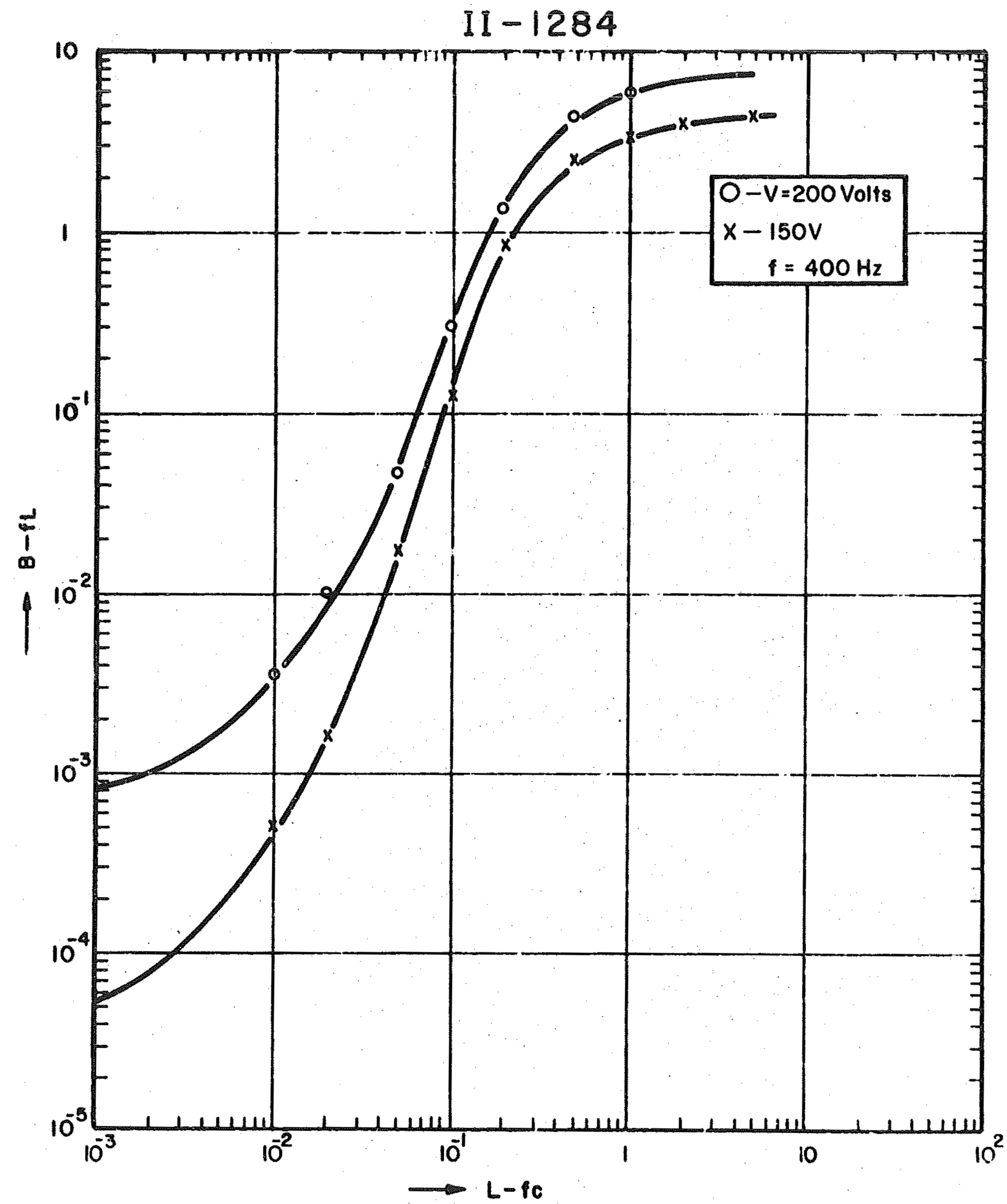


FIGURE 16: Transfer Characteristics of Light Sensitive Image Amplifier

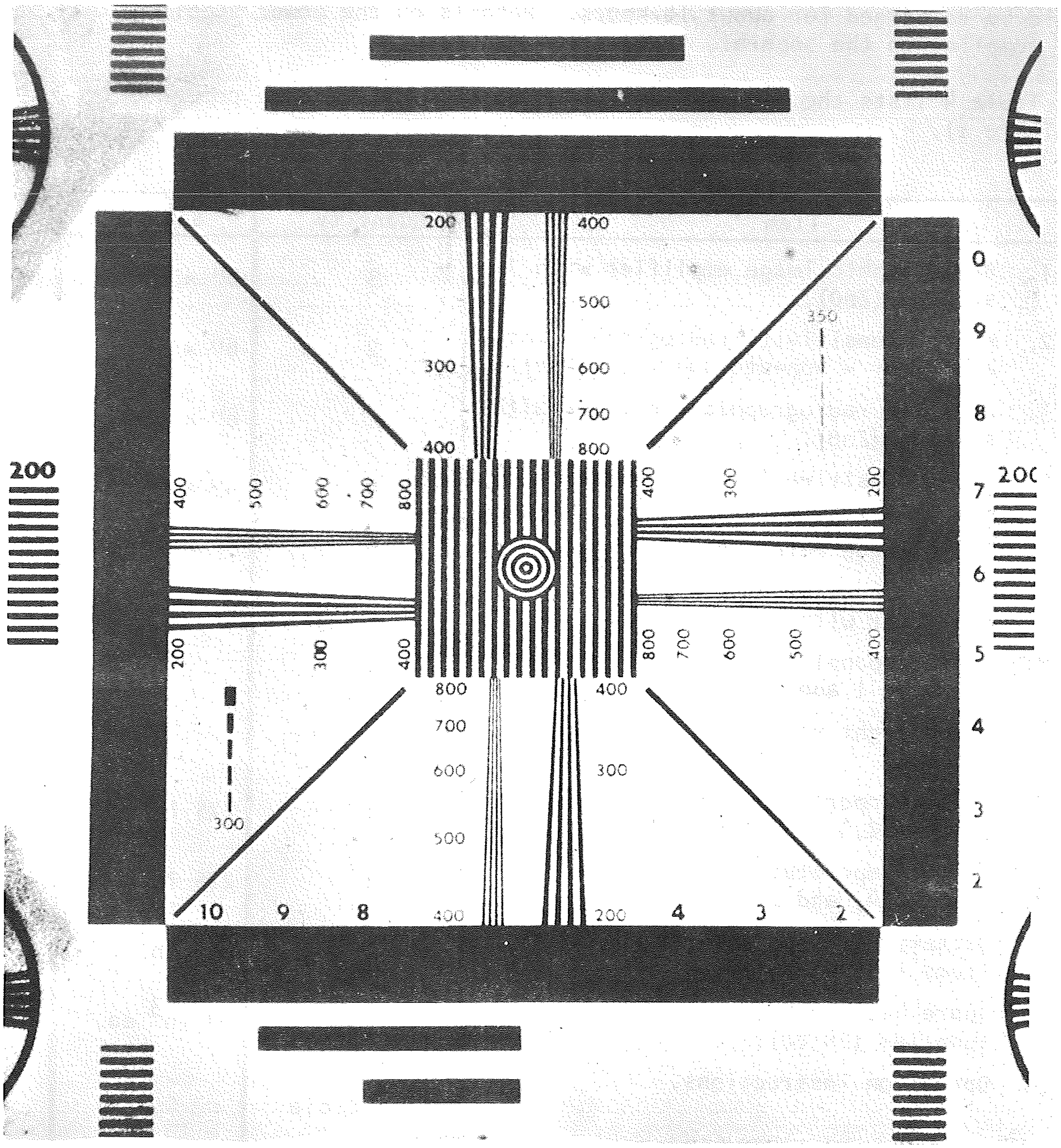


FIGURE 17: Photograph of Output Image of a TV Test Pattern on a Light Sensitive Image Intensifier

The batteries were sufficient for about 30 minutes loading and they could be recharged for about 16 hours. Details on the power supplies are supplied in the separate Instruction Manual.

Table 4 lists the hardware delivered to NASA-MSFC (to be compared to Table 1).

Item	Quantity	Size
1. Radiographic image amplifier with storage (ZnO).	3	8" x 10"
2. Higher sensitivity radiographic image amplifier - non-storage (CdS/CdSe).	2	6" x 9"
3. Flexible radiographic amplifier with storage (ZnO).	1	8" x 10"
4. Light sensitive image amplifier without storage (CdS/CdSe).	4	4" x 6"
5. Thorn image retaining (storage) panel.	4	4" x 6"
6. Experimental light sensitive image amplifier with storage (ZnO).	1	2" x 2"
7. Storage panel heating unit (eraser) for item 1 above.	1	
8. Point light source - LED Monsanto type MV3.	1	
9. Battery operated power supply for items 1,2,3,4,5, and 6 above.	1	225 in^3
10. Battery operated power supply for items 2,4, and 5 above.	1	225 in^3
11. Battery operated power supply for items 1,3, and 6 above.	1	225 in^3
12. Spare batteries (Ni-Cd) for power supplies (24 Volts).	3	44 in^3 ea.
13. Operation instructions.	23+ Reproducible	
14. Final Report.	23+ Reproducible	

TABLE 4. ITEMS DELIVERED TO MSFC

SECTION 6

DISCUSSION

The efforts of the work reported here were directed toward the development of two different solid state image amplifier systems: (1) a radiographic and (2) a light sensitive system. Though the required characteristics of the two systems were quite different, the approach for reaching the goal in both cases was principally the same: by employment of a sandwich type PC-EL construction. The materials, however, and especially the PC material and its optoelectronic characteristics, were different for the two systems. Also, PC materials with different characteristics have to be developed for three different kind of amplifier screens in the first group: radiographic amplifier (1) with storage, (2) without storage (both on solid substrates), and (3) with storage on flexible substrate. Properly chosen materials enabled the requirements for all three systems to be closely approached with only two different fabrication technologies. One technology made use of sintered CdS-CdSe PC powders, the other of ZnO plastic embedded powders. The first method was used for building radiographic and light sensitive amplifiers without storage. In the fabrication process first the PC powder was deposited by a settling method (properly mixed with dopants, depending on the required characteristics), sintered at about 500°C (934°F) temperature, then sprayed with a plastic embedded EL powder layer (for more details see Appendices B and E). The second method, used for fabrication of storage type panels (radiographic or light sensitive) both on rigid (glass) and on plastic substrates, involved depositing first the plastic embedded EL layer on the substrate by spraying, and then doctor blading (or spraying) the plastic embedded PC layer (ZnO) on it (for details, see Appendices A and D). There was not high temperature baking in this method. The maximum processing temperature was 130°C (265°F).

Storage light sensitive amplifiers were constructed by superimposing a non-storage type CdS-CdSe panel on a Thorn image retaining panel. This method was successfully pursued: however, just before the termination of the program, it was found that dyeing the ZnO powder with light sensitive organic dyes as Rhodamine-B, Fluorescein or Eosyn-Y, light sensitive storage panels can be made in the simple PC-EL sandwich construction. Though the sensitivity of these panels was quite low (threshold 10 fcs) one of them has been delivered to NASA-MSFC for preliminary experiments. It is hoped that with more systematic work the sensitivity of these panels can be increased.

The first requirement for the storage panels was: long storage times for viewing (more than 10 minutes) and fast erasure time (less than 2 minutes). The ZnO type storage panels (both the radiographic and the visible), when driven by 60 Hz, had a viewing storage time (time where the brightness drops to 1/3 of the original brightness) of 10 to 60 minutes, depending on the preparation of the ZnO powder and some construction parameters of the panel. With 400 Hz driving voltage the viewing storage time was smaller by a factor of about 4. After this time, the resolution of the picture, even with brightness reduction, was still very nearly the same as in the beginning, consequently the practical storage time was longer by a factor of 3 to 4. On special screens, pictures were visible after more than 24 hours.

Erasure of the images on the ZnO type panels can be accomplished by heating the panel (1) in a furnace at about 100°C (212°F) or (2) by an infrared lamp, or (3) electrically. The third method consists of applying a voltage on two opposite ends of one electrode (tin-oxide coating is preferred). A heating time of about 5 to 30 minutes depending on the storage time, was needed in the first method for the erasure of the image. Two to three times faster erasure was accomplished by the third method without deteriorating the panel. Higher temperatures on the ZnO give faster erasure, but can cause deterioration of the contrast. The second method was not systematically examined, but probably could be as fast as the third method. Practically, it is recommended that the panels be prepared with the shortest permissible storage time, so that erasure time can be minimized.

The resolution of the radiographic storage panels was better than 300 lines/inch (6 line pairs/mm), that of the light sensitive panel about 200 lines/inch (4 line pairs/mm).

The contrast sensitivity of the radiographic panels closely approached the 2% of thickness definition required, however, the brightness of the image was below the necessary value for detecting a small hole of 2T diameter on a 2% penetrameter per MIL-STD-453. On a 0.25" thick aluminum plate, the outline of the penetrameter and a hole of 0.25" diameter were visible. Direct contact of photographic film with amplifier screen, plus further evaluations with high current, low voltage inputs may yet reach the 2%T required. Contrast sensitivity enhancement, by cascading a radiographic amplifier screen (CdS/CdSe) with the new light sensitive ZnO image intensifier panel, is promising and should also be pursued.

The absolute sensitivity of the radiographic storage amplifier screen is similar to that of high resolution radiographic films.

The flexible radiographic amplifier screens have similar opto-electronic characteristics to those built on glass substrates. The smaller samples (2" x 2") could be bent on a 2" radius without damage, but large area panels deteriorated after repeated bending and need some improvements in fabrication technology or change in materials.

One problem, not yet solved in these ZnO type amplifier screens, both flexible and non-flexible, is the protection of the panel, specifically the EL layer, against humidity.

The non-storage type radiographic amplifier screen built with a mixture of CdS and CdSe have characteristics similar to the storage types with the exception of the rise time and decay time constants of the image. These time constants depend mostly on the composition of the PC layer. They increase as the CdS content increases. The best screens, containing 25% CdS, 75% CdSe had time constants in the range of a second. The protection of these panels was solved by sealing, with epoxy, a thin glass plate on top of the layers.

The light sensitive combined system has the advantage of a fast erasure. The disadvantages are: lower resolution, mirror image and the impossibility of observation during exposure time. Consequently, the new experimental ZnO light sensitive storage panel, in spite of the slower erasure time, should be developed for most applications.

Three portable self-contained power supplies with rechargeable Ni-Cd batteries were constructed giving the necessary frequency and variable voltages: 400 Hz ranging from 0-310 volts for the PC-EL panels, and DC ranging from 75-100 volts for the Thorn panel. Their weight was slightly more than 11 pounds each and volume was 225 cubic inches.

The main applications of the storage radiographic amplifier screens is in radiographic non-destructive testing. They can substitute for photographic radiography, when no record keeping is needed. Their main advantages are the immediate viewing (without any processing) and the low cost.

Since the application of the electric field is necessary only for viewing, possible use of the flexible panel could be for dental radiography.

When record keeping is needed, the storage panel could easily be photographed on light sensitive inexpensive films, and still offer some advantages over the photographic radiography, such as speed and costs.

Besides the application for non-destructive testing, the storage solid state radiographic screens could find some use in special medical problems, mostly in military field applications.

The non-storage type radiographic amplifier can be used in applications where fluoroscopic screen or vacuum type X-ray image intensifiers and TV systems are used. It has many advantages compared to the above systems. The simple fluoroscopic screen has low sensitivity, contrast and resolution. The complex system with X-ray intensifier tube, which replaced the fluoroscopic screen in medical radiology, is more sensitive; but it is large and heavy, has limited area imaging capability, and is expensive. It also has low contrast and resolution.

The solid state radiographic amplifier is almost as simple and lightweight as the fluoroscopic screen, has a moderate gain, and has much higher resolution and contrast than the other two systems. One of the few objectionable characteristics is its slow response, another is its gain which is lower than the vacuum type intensifier. However, for non-destructive testing and in a large number of medical applications, these characteristics are acceptable. By improving the sensitivity of these panels, more applications could be found in medical radiology.

Since the CdSe is sensitive in the near infrared, these amplifier panels can be used for the detection and imaging of infrared rays up to about 1.1 μm. Particularly good results were obtained by imaging of pulsed laser beams. In another application, cascading a solid state intensifier panel with a camera tube or image intensifier tube, extended the usefulness of these vacuum devices to longer wavelengths[14].

The light sensitive storage panel can be employed effectively in the display of a recorded image generated by a moving light. Light emitting injection EL diodes (LED) can be used as scanning and modulation light sources.

The state of the art now offers the possibility for development of numerous applications for these different types of solid state intensifiers.

SECTION 7

RECOMMENDATIONS

The developed radiographic intensifier screens and light sensitive panels can be used with some compromise, in the intended applications. Some experiments carried out during this work indicate that improvements can be achieved in some characteristics with a limited effort, which would increase the usefulness and application of these solid state intensifiers.

(1) The fact that the use of EL layers with higher discrimination ratio would increase the contrast sensitivity of the amplifier panel suggested the application of evaporated EL films, which have higher discrimination ratios than those of the plastic embedded EL layers. The possibility for improving the contrast of such EL films in ambient light was also proved by a small sample, obtained from the Sigmatron Corporation. However, this second improvement is not limited to evaporated EL films, it could be applied to plastic embedded EL layers as well and would be equally effective when improved viewing of these panels is required in ambient light.

Therefore, it is recommended that the contrast enhancing technique (in ambient light) for these intensifier panels be developed and consideration be given to the use of evaporated EL layers for improving contrast sensitivity.

(2) Some success has been obtained in making light sensitive storage intensifier panels in an all plastic construction using dyed ZnO powders. The sensitivity of these intensifiers was, however, somewhat low and would need some improvement.

Therefore it is recommended that higher sensitive ZnO powders be developed for the visible range, to increase the sensitivity of the light sensitive storage panels.

(3) To be able to detect 2T holes on 2% penetrameters per MIL-STD-453, higher output brightness will be needed. This higher brightness can be obtained by cascading a non-storage type radiographic amplifier (CdS/CdSe) with a light sensitive storage intensifier panel (ZnO). The technique of integrating these two panels in one unit is straightforward and will not present difficult problems.

Therefore a moderate effort is recommended for the fabrication of such cascaded intensifiers, after the sensitivity of the ZnO light sensitive storage panel is appropriately improved.

(4) The ZnO storage panels need some protection against humidity to increase the life of these panels.

Therefore it is recommended to study the maintenance (life time) of the ZnO storage panels and develop the method of protection for increasing the life of these amplifier panels.

(5) Though the construction of the solid state amplifier systems was planned with future space application in view, it was necessary to satisfy opto-electronic specifications first then, if successful, proceed with a system for use in the space environment.

A principal effort in building a system, considering space applications for non-destructive testing, is recommended as early as practical in the space station/space shuttle missions.

(6) Finally, some possible applications of these amplifier panels in medical, industrial, military and educational fields are listed:

(a) Non-storage type radiographic amplifiers:

Improved fluoroscopy.

Light-weight radioscopy in military field applications, using radioactive isotope source.

Inexpensive T.B. detection system (amplifier screen + 35mm camera) requiring low X-ray dose.

Use in hazardous terrestrial oceanographic and space environments.

(b) Non-storage type light sensitive image intensifiers:

Back-lighted projection screens.

Displays with increased brightness, where brightness of original image is restricted, such as cathode ray tubes or projection systems.

(c) Storage type radiographic amplifier:

Replacing expensive photographic radiography where record keeping is not needed, or using less expensive film for records.

Uses in field, listed under (a).

(d) Storage type light sensitive amplifier:

Replacing film or recording paper by using a point light source to write.

Display in ultrasonic and other non-destructive testing equipment to replace "X-Y" area scan recorder readout.

Clean and noiseless writing board.

The extent of these applications depend largely on the characteristics, availability, and price of these panels. Since their fabrication is quite simple, especially the storage panels, the price consideration looks very favorable, and quantity fabrication of some of these panels will probably be started in the near future. Several non-storage type radiographic amplifiers have already been sold.

SECTION 8

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APPENDIX

APPENDIX A

PREPARATION OF ZnO POWDERS

1. Weigh 81g pure ZnO powder and mix 71mg $NaSO_4$ with it and load it into an open quartz boat.

2. Bake the mixture in a furnace with slowly flowing air (2 CFH) at 950°C (1742°F) for two hours.

3. After the powder cooled down, place it in a Waring blender 1/3 full with deionized water and blend it for 1 minute at high speed.

4. Pour mixture into 1 liter Erlenmyer flask, let the powder settle and decant the water.

5. Repeat rinsing, settling and decanting two other times with deionized water.

6. Rinse with 2-propanol, settle and decant two times. On second 2-propanol rinse, ultrasonically agitate for 3 minutes.

7. Filter through Milliport filter (type AAWP4700-AA-0.8μ).

8. Dry in forced air oven at 135°C (275°F) for 30 minutes.

9. Shake powder through 200 mesh sieve.

APPENDIX B

PREPARATION OF SINTERED CdSe PC LAYERS

1. Mixture With 10% CdS

The preparation of the sintered CdSe layer can be divided into three parts. Accordingly, the schedule of preparation is described below:

(a) Mixing and Prebaking the Powder

1. Weigh 90 grams of CdSe and 10 grams of CdS powder (G.E. electronic grade) and mix it in a pyrex beaker.

2. Place the well mixed powder in a quartz boat and heat it slowly in nitrogen atmosphere until the temperature reaches 1075°C (1966°F). Bake it for 30 minutes at this temperature and cool down still in nitrogen atmosphere.

3. Grind the material in diamonite mortar.

4. Weigh 4 grams of dry $CdCl_2$, place it in a 100 ml pyrex beaker and dissolve it in about 20 ml deionized water.

5. Weigh 10 milligrams of $CuCl_2 + 2\ H_2O$ (Fisher Certified), transfer to a clean 15 ml beaker and dissolve it in about 5 ml deionized water.

6. Add enough deionized water to the CdSe + CdS baked powder to form a very thick paste.

7. Add the $CdCl_2$ solution to the CdSe + CdS paste with thorough stirring.

8. Add the $CuCl_2$ solution to the CdSe-CdS-$CdCl_2$ mixture with thorough stirring.

9. Evaporate the water from the mixture in a forced draft oven at 100°C (212°F).

10. Prebake at 505°C (940°F) for 1 hour in a quartz dish with a cover.

11. After cooling, grind the material in a diamonite mortar, and sieve through a 200 mesh screen.

(b) Settling

1. Weigh about 50 grams of the prepared CdSe-CdS powder, transfer it to a ceramic ball milling jar, mix about 100 ml Xylene with it and ball mill for five to sixteen hours.

2. Clean the substrate glass plates as described in Appendix F.

3. Place the substrate glass plates in a perfectly horizontal plane at the bottom of a 10'' x 12'' glass jar.

4. Fill the jar with a 0.1% ethyl cellulose Xylene solution to about 5'' height above the substrate glasses.

5. Pour the ball milled PC mixture in the settling jar and let it settle until the Xylene clears up (about 1 to 2 hours).

6. Siphon off cushion and let panels dry in tank 10 to 16 hours.

7. Remove panels from tank and preheat slowly to about 100°C (212°F) on a hot plate for about half an hour.

8. Transfer panels to forced air oven and bake at 135°C (275°F) for half an hour.

c. Sintering

1. Place panel on a Vycor plate and cover with a pyrex dish.

2. Bake in a furnace of 510°C (950°F) for 40 minutes.

3. Remove panel from furnace and allow to cool under a strong airflow on the pyrex dish.

II. <u>Mixture With 25% CdS</u>

The preparation schedule is the same excepting the following:

a. 1. Weigh 75g of CdSe and 25g of CdS powder, etc.

5. Weigh 35mg of $CuCl_2$+$2H_2O$, etc.

III. <u>Mixture With 50% CdS</u>

Here the following changes have to be made:

(a) 1. Weigh 50g of CdSe and 50g of CdS powder, etc.

5. Weigh 40mg of $CuCl_2$+$2H_2O$, etc.

APPENDIX C

PREPARATION OF EL LAYERS

The EL layers were deposited by spray coating. A "deVilbiss" type EX spray gun with suction feed and a pressure of 18 psi nitrogen was normally used.

The schedule of the preparation of the EL layer was the following:

1. Spray a layer of spray mixture No. 1 or No. 1a (see below) onto the substrate. The layer should be good and wet but not running.

2. Let the layer air dry for a minute or two and bake it in a forced air furnace at 135°C (275°F) for 10 minutes (100°C (212°F) if 1a was used).

3. Repeat steps 1 and 2 three to four times so that altogether four to five EL layers were sprayed.

4. Bake for 30 minutes instead of 10 per 2 above, after the spraying of the last layer.

5. Spray a thin layer (3 to 4 layers) of clear coat (mixture No. 2, or 2a if 1a was the EL mixture) on top of the phosphor layer for increased electric strength and smoother surface.

6. Give a final heat cure of 30 minutes at 135°C (375°F) (100°C (212°F) if 2a was used).

7. In the case when the EL layer is on top of the PC layer, evaporate a semi-transparent conductive lead-oxide and gold film in high vacuum on top of the sprayed layers. With a substrate to boat distance of 18 inches, 64mg of PbO is evaporated first, followed by the evaporation of the Au. Latter evaporation is monitored by measuring the resistance of the deposited layer on a microscope slide and the evaporation is stopped when this resistance is about 50 ohms/square.

Composition of spray mixtures:

1. Phosphor-plastic spray mixture:

   27g Westinghouse VB-241P EL phosphor.
   90 ml 5% solution of cyanoethyl starch (CS)*
   90 ml 5% solution of cyanoethyl sucrose (CES)*

* Sold by Eastman Chemical Corporation

Plastic solutions (5%)

40g plastic (CS or CES)
220 ml dimethyl formamide (DMF)
580 ml acetonitrile

2. Clear coat:
1:1 mixture of 5% CS and 5% CES solutions (see formula above).

(1a) Phosphor-plastic spray mixture with Ucilon*

27g Westinghouse VB-241P EL phosphor.
36 ml Ucilon White Type 400-9.
144 ml Ucilon Thinner Type 400-T.

(2a) Ucilon clear-coat:

36 ml Ucilon White Type 400-9.
144 ml Ucilon Thinner Type 400-T.

*Sold by M & T Chemical, Inc., Rahway, New Jersey

APPENDIX D

PREPARATION OF STORAGE AMPLIFIER SCREENS

I. On Glass Substrate (Pyrex, Corning Glass Type 4470, Tin Oxide Coated)

1. Clean glass plate by wiping it with $CaCO_3$ water paste, rinse in deionized water and vapor degrease and dry in 2-propanol vapor.

2. Spray an EL layer on the substrate as described in Appendix C, Schedule 1-4, using mixture la.

3. Blade the ZnO mixture (see paragraph III below) on top of the EL layer with Shandon blading machine with thickness setting of 15 mils.

4. Let the bladed layer dry at least 24 hours at room temperature.

5. Bake the panels for 60 minutes at 130°C (265°F).

6. Paint 3 layers ucilon 25% on 2 opposite edges and on top of the ZnO layer.

7. Apply Emerson Cummings V-91 silver epoxy to the two ucilon coated edges on top of the ZnO layer.

8. Bake 30 minutes at 100°C (212°F).

9. Evaporate a PbO+Au electrode on top of the ZnO layer as described in Appendix C, Schedule 7, excepting that the Au evaporation is continued until the monitoring slide shows about 10 ohms/square.

10. Clean two opposing edges of the glass plate (other than the one with the silver epoxy) and cement a No. 18 stranded copper wire all along both edges with Emerson-Cummings V-91 silver epoxy. (These wires will serve for heating the tin oxide electrod to erase the stored image).

11. Attach flexible No. 22 stranded insulated wire to one silver epoxy coating, which gives connection to the top electrode. Connect another flexible wire to one of the heater electrodes. These two wires are the leads to the driving voltage of the amplifier panel.

12. Mount panel in a wood picture frame. Fix leads to frame properly.

II. On-Plastic Substrate ("Aclar sheet, Allied Chemical)

1. Clean plastic sheet by vapor greasing and drying in 2-propanol vapor.

2. Apply Emerson-Cummings V-91 silver epoxy to two opposite edges of substrates. Cover the full length of the edge with 1/8" wide strip of epoxy and bake 30 minutes at 100°C.

3. Evaporate a PbO-Au semitransparent conductive film to the plastic sheet as described in Appendix C, Schedule 7. Continue to evaporate on top of the gold film another film of PbO.

4. Spray an EL layer as described in Appendix C, Schedule 1 to 4 using mixture 1.

5. Spray ZnO spraying mixture (see below) on top of the EL layer to a thickness of at least 3 mils.

6. Bake the panel for 60 minutes at 130°C.

7.
8.
9.
10.

Same as Schedules 6, 7, 8, 9 of Paragraph I for glass substrate.

11. Attach one flexible wire to the first electrode and another to the top electrode.

III. Composition of ZnO Mixtures for Radiographic Amplifiers

(a) Blading mixture.

1. Mix 100g ZnO powder (prepared as described in Appendix A)
   16.7g silicone resin DC-804
   18.4g diethyl carbitol

2. Ball mill the mixture with 6 ceramic balls in a 180 ml glass bottle for one hour.

3. After taking out the balls, agitate the mixture for about 3 minutes with ultrasonic agitation and use it for blading.

(b) Spray mixture.

1. Mix 100g ZnO powder (see Appendix A)
   100 ml Xylene
   50 ml Amyl Alcohol
   33.4g plastic binder PCB-4.

Formula for plastic binder PCB-4:

240g silicone resin DC-804
100g Dibutyl Phtalate
100g Xylene
8g Butanol

2. Ball mill the mixture with 80 3/8" size steel balls for 2 hours.

3. Take out the balls and spray.

IV. Composition of ZnO Mixture for Light Sensitive Panel

1. Mix 100g ZnO powder (NJZ type CT-011-55)
   50mg Rhodamine B
   16g DC-804 Silicone Resin (60%)
   18g Diethyl Carbitol

2. Ball mill the mixture for 2 hours.

3. Take out the balls and use it for doctor-blading.

APPENDIX E

PREPARATION OF RADIOGRAPHIC AND LIGHT SENSITIVE AMPLIFIERS WITHOUT STORAGE

1. Substrate Preparation

   a. Clean glass plate as described in Appendix F.

   b. Platinum coat center two-thirds of two opposing edges.

   c. Fire platinum coat at 525°C (977°F) - 1 hour in air.

2. Settling of the PC powder.

   See Appendix B, Part (b).

3. Sintering

   See Appendix B, Part (c).

4. Evaporate 1.5g CdSe at 18 inch distance in high vacuum on top of the sintered CdSe layer.

5. Spray 3 layers of 5% Ucilon White* Type 400-9.

6. Bake in forced air oven at 135°C (275°F) for 30 minutes.

7. Brush 3 layers of 25% Ucilon White on 4 edges.

8. Repeat step 6.

9. Spray 4 layers of green EL phosphor, Westinghouse type VB-241P, and 3 layers of clear coat (steps 1 to 6 of Appendix C) using mixtures 1 then 2.

10. Brush 3 layers of clear coat on 4 edges only.

11. Bake at 135°C (275°F) for 30 minutes in forced air oven.

12. Apply Emerson-Cummings V-91 silver epoxy with rubber pad applicator to the two opposing edges not covered with platinum. This will connect to the evaporated gold layer.

*Made by M & T Chemicals, Inc., Rahway, New Jersey

13. Bake at 135°C (275°F) for 1 hour

14. Evaporate top transparent gold electrode PbO + Au (step 7 of Appendix C).

15. Pretest

    a. Sensitivity
    b. Time response
    c. Imperfections, spots, bright edges.

16. Cover electrode edges on substrates with 1/16 inch wide masking tape to protect electrode from epoxy.

17. Spray several coats of Krylon crystal clear spray coating, Type 1302, on top of gold layer.

18. Bake panel for 30 minutes at 100°C (212°F).

19. Attach wires to two electrodes (one to tin-oxide, other to gold) with Emerson-Cummings V-91 silver epoxy.

20. Apply about 32g (for 6" x 9" panels) of Emerson-Cummings No. 1266 epoxy to the center of the coated substrate.

21. Place a precisely cut cover glass against the epoxy on substrate and carefully align.

22. Wipe excess epoxy from edges as it squeezes out and apply a flat steel plate, larger than the panel, on top of cover glass, as a weight heavy enough to hold cover glass parallel and near the panel during cure.

23. Allow to cure at room temperature for 16 hours and remove excess epoxy with razor blade, taking care not to damage electrodes.

24. Remove masking tape from edges.

APPENDIX F

CLEANING OF GLASSWARE AND SUBSTRATES

1. Place glass in a beaker of deionized water dependent upon the size of the piece and rinse thoroughly by overflow.

2. Drain off the rinse water to allow introduction of approximately 5-10% water solution of each of formic acid and hydrogen peroxide. The following solution was generally used:

   1250 cm^2 water
   100 cm^3 formic acid
   250 cm^3 hydrogen peroxide

3. Heat this solution to the 70-80°C (160-175°F) range, being careful not to allow the temperature to exceed 80°C (175°F). When over 75°C (168°F) has been reached, remove the beaker from the hot plate and allow to react at least for 30 minutes. The temperature will maintain itself for this period in a useful range. At the end of this time overflow deionized water rinse for 15 minutes.

4. Ultrasonically clean in deionized water for 5 minutes.

5. Ultrasonically clean in electronic grade isopropanol for 5 minutes.

6. Place glass piece above boiling isopropanol, where it will heat up. When taken out it dries immediately.

APPENDIX G

TESTING PROCEDURE OF IMAGE AMPLIFIERS

I. Non-Storage Type Panels

Since characteristics measured in the visible light region are correlated to those in the X-ray region, light measurements were frequently used in testing the radiographic amplifier also. Specifically, tungsten light (mostly 2870°K color temperature) was used in measuring the resolution, transfer characteristic curves, spottiness, graininess, and uniformity of the image amplifier. For radiographic amplifiers, a few points of the transfer characteristic curves and the contrast sensitivity were measured with X-rays.

Specifications of the testing procedure are described in the following. The usual driving voltage and frequency of the image amplifier were: 115 Volts and 400 Hz, unless otherwise specified.

1. Resolution

   (a) A RETMA TV resolution chart was projected with a slide projector onto the image amplifier and the resolution limit was evaluated visually from the output image.

   (b) A resolution test pattern made of 0.05mm thick lead was used for radiographic amplifier screens.

2. Transfer Characteristic Curves

   (a) A 2870°K color temperature tungsten light source with continually changeable calibrated light intensity was used for input at intensities at 10^{-2}, 2×10^{-2}, 5×10^{-2}, 10^{-1}, 2×10^{-1}, and so on. The output brightness was measured with a Spectra brightness meter, type UC1/2. Curves with driving frequencies of 60, 400, and 2000 Hz were measured.

   (b) For the radiographic amplifiers the X-ray output of 45 kV and 70 kV rectified X-ray generator (Philips MG100) was used for 6 points of the transfer characteristic curves at 400 Hz driving frequency on the image amplifier. The X-ray intensity was measured with a Victoreen electrostatic dosemeter.

3. The contrast sensitivity was evaluated visually by imaging a set of 4 aluminum discs 0.1 inch thick each, having about 1/4" x 1/2" size holes corresponding to 3, 4, 5, and 6% defects, and with a 2% aluminum penetrameter on a 1/4" thick aluminum sheet, in accordance with MIL-STD-453.

4. Time Constants. The time constants were measured with visible light at around the center point of the transfer characteristics. The equipment used for these measurements was: a millisecond fast pneumatic shutter on the calibrated light source (used in test procedure 2a), and a storage cathode ray oscilloscope.

II. Storage Type Panels

Sensitivity and storage time were measured by radiating the panel with a 45 kV rectified X-ray source for 60 seconds. The driving frequency on the panel was 60 or 400 Hz and the voltage was as high as possible, i.e. until the background light was not much higher than 10^{-2} fL. The brightness of the output was recorded with a calibrated CdS photocell during the build-up and the recording was continued generally until the brightness dropped to 1/3 of its maximum value. The elapsed time (without irradiation) was called the storage time.

The panels were heated before measurements in a 100°C furnace, for complete erasure of the previous image.